The low-background germanium counting facility Gator for high-sensitivity ɣ-ray spectrometry

Zurich PhD Student Seminar

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Particle Astrophysics
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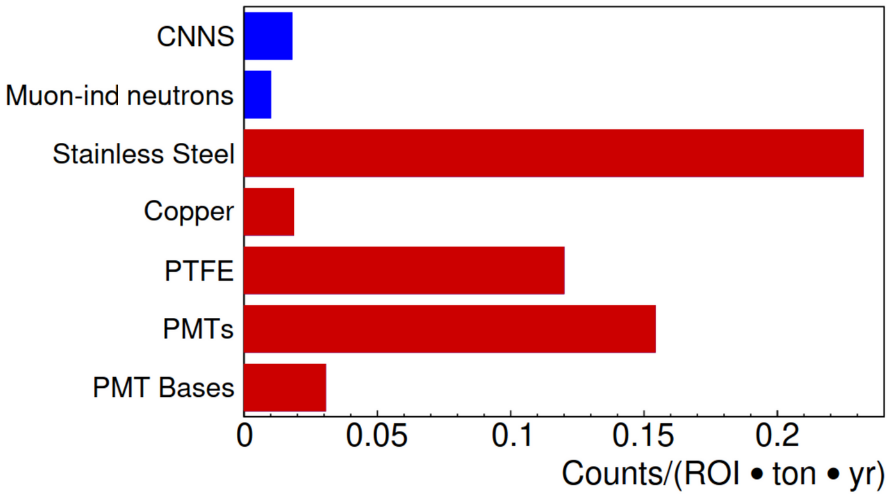
Motivation

- Required low backgrounds in rare event searches (e.g. DM, $0\nu\beta\beta$)
- Germanium spectroscopy: non-destructive and high resolution screening method for material radioassay
- Selection of radiopure detector materials and precise background simulations
- Gator facility used for...
  - XENON100, XENON1T and XENONnT, GERDA and LEGEND-200
  - Future: LEGEND-1000 and DARWIN

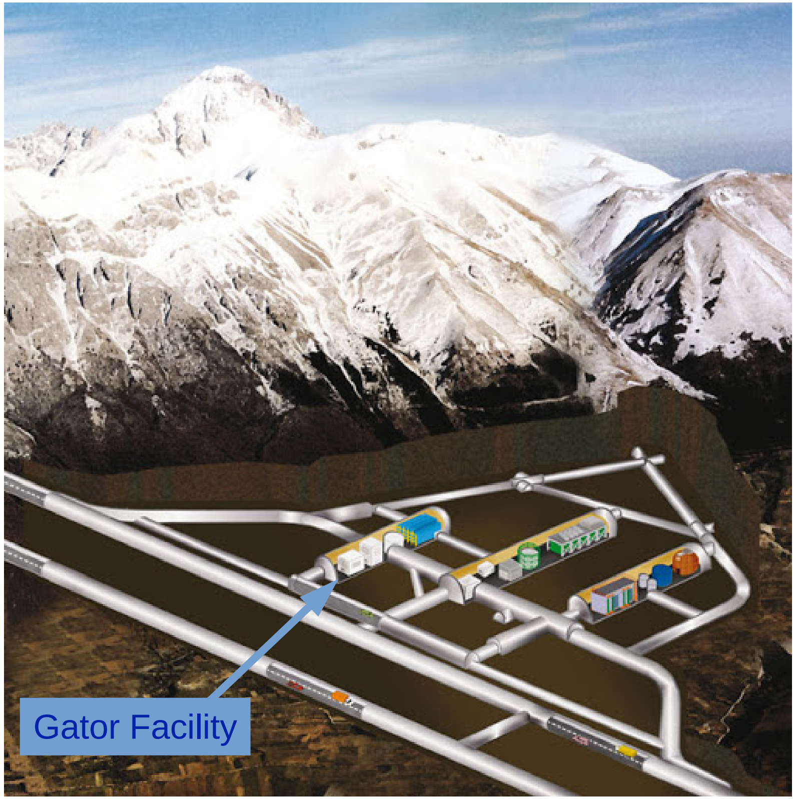


Nuclear recoil backgrounds in XENON1T from materials (red), predicted from screening measurements, and external sources (blue) [1]

[1] Eur. Phys. J. C77 (2017) 890

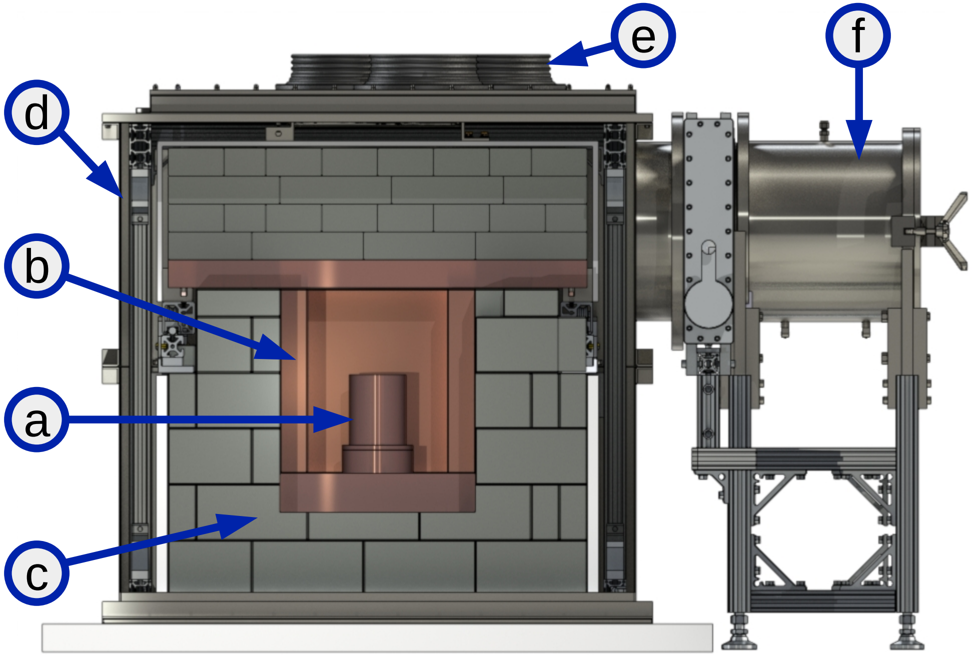
The Gator Facility

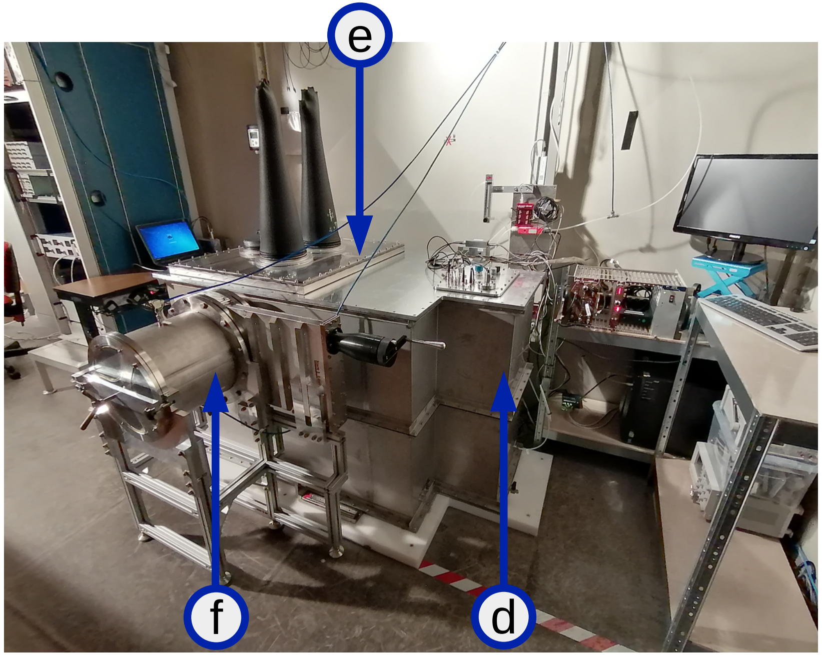
- Low-background germanium counting facility for high-sensitivity γ-ray spectrometry [2]
- Located at the Gran Sasso underground laboratory in Italy (LNGS) at a depth of 3600 m water equivalent
- Core: p-type coaxial high-purity germanium (HPGe) detector with 2.2 kg sensitive mass and a relative efficiency of 100.5%
- Sample chamber volume: $25\times25\times33$ cm^3
- Recent upgrades to decrease background level, noise contribution in low-energy region, facilitate sample handling process



[2] JINST 17 (2022) P08010

The Upgraded Gator Detector

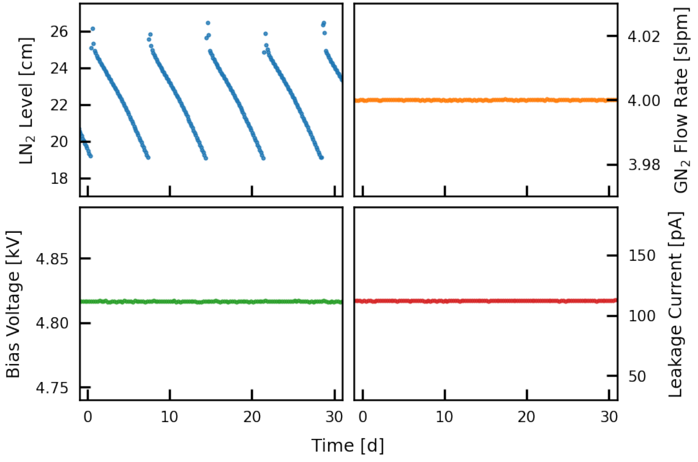


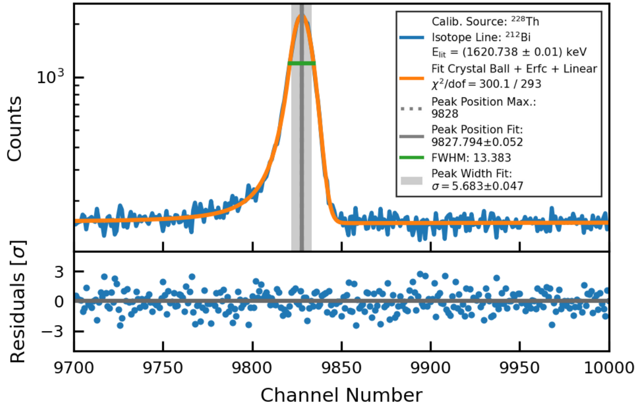


(a) HPGe detector inside Cu-OFE cryostat (cooled with LN_2 via copper coldfinger), **(b)** OFHC Cu cavity, **(c)** lead shield, polyethylene sheet, **(d)** airtight stainless steel enclosure (purged with GN_2), **(e)** glove ports, **(f)** sample load lock

Detector Operation and Performance

- Stable operation for over 10 years
- Remote monitoring (incl. alarms) of operations parameters to ensure detector stability and data quality
- Regular calibrations of the detector with radioactive sources (e.g. ^{228}Th, ^{137}Cs, or ^{60}Co) or high-activity samples
  - FWHM at 1332 keV: (1.98±0.07) keV (Maeve: 3.19 keV [3], GeOroel: 1.85 keV [4])
  - Verification of simulated efficiencies and consistent activities related lines



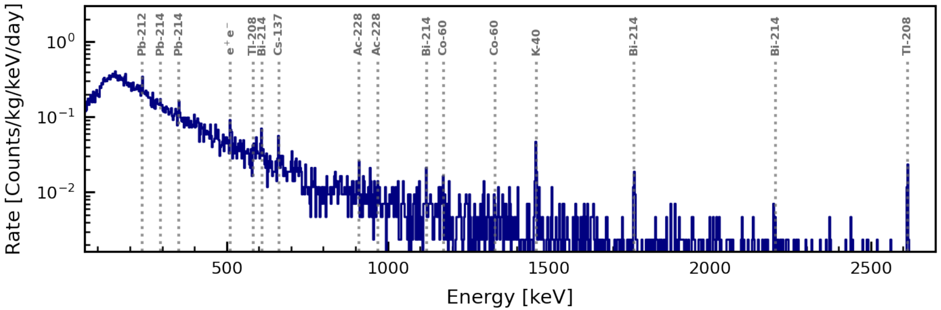


[3] Eur. Phys. J. C80 (2020) 1044
[4] Bandac, “Ultra-Low Background Services in the LSC”, DS-Mat Meeting, GSSI, 2019

Background Contributions

- Integrated background rate in the energy region 100-2700 keV [2]:
  (82.0±0.7) $d^{-1}kg^{-1}$;
  as compared to value from 2010 [5]:
  (102.8±0.7) $d^{-1}kg^{-1}$;
  stable within runs (χ^2/ndf ≈ 1)
- Low energies (≲ 35 keV, below ROI):
  - electronic noise
- Higher energies:
  - detector & shielding materials
  - environmental radon

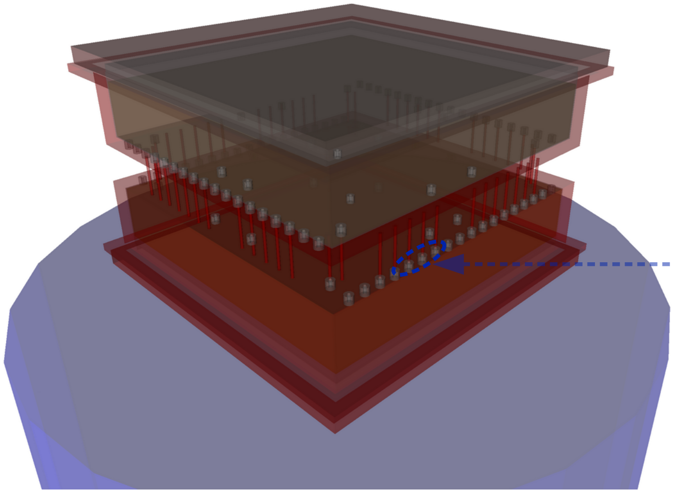
Energy [keV]	Isotope	Rate '21 [d^{-1}]	Rate '10 [d^{-1}]
351.932	Pb-214	0.41 ± 0.17	0.7 ± 0.3
609.312	Bi-214	0.26 ± 0.10	0.6 ± 0.2
1120.29	Bi-214	< 0.28	0.3 ± 0.1
1764.49	Bi-214	0.14 ± 0.06	0.08 ± 0.06
661.657	Cs-137	0.19 ± 0.09	0.3 ± 0.1
1173.24	Co-60	< 0.27	0.5 ± 0.1
1332.51	Co-60	< 0.21	0.5 ± 0.1
1460.88	K-40	0.28 ± 0.08	0.5 ± 0.1
2614.51	Tl-208	0.19 ± 0.05	0.2 ± 0.1



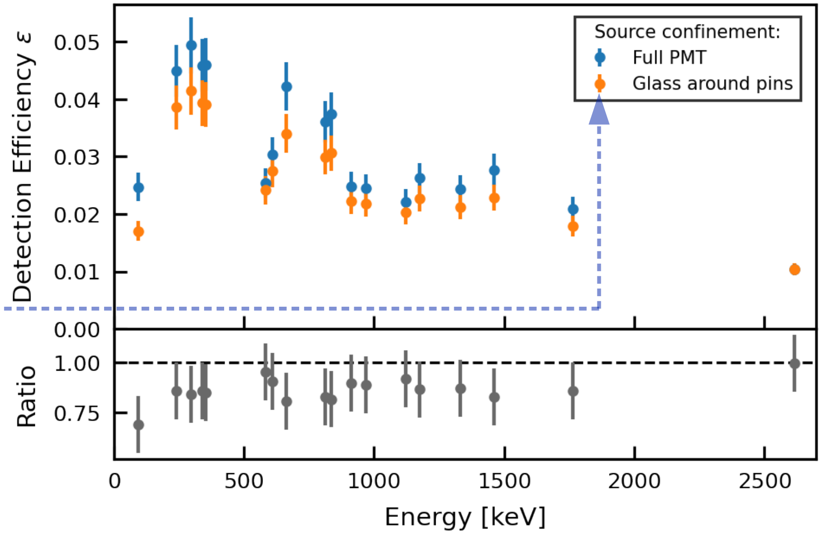
[2] JINST 17 (2022) P08010, [5] JINST 6 (2011) P08010

Sample Simulation and Analysis

- Determination of the material-, geometry-, and energy-dependent detection efficiency ε of the respective γ-lines through GEANT4 Monte Carlo simulations for each sample



Simulated R12699 PMTs on detector



Resulting detection efficiencies lines

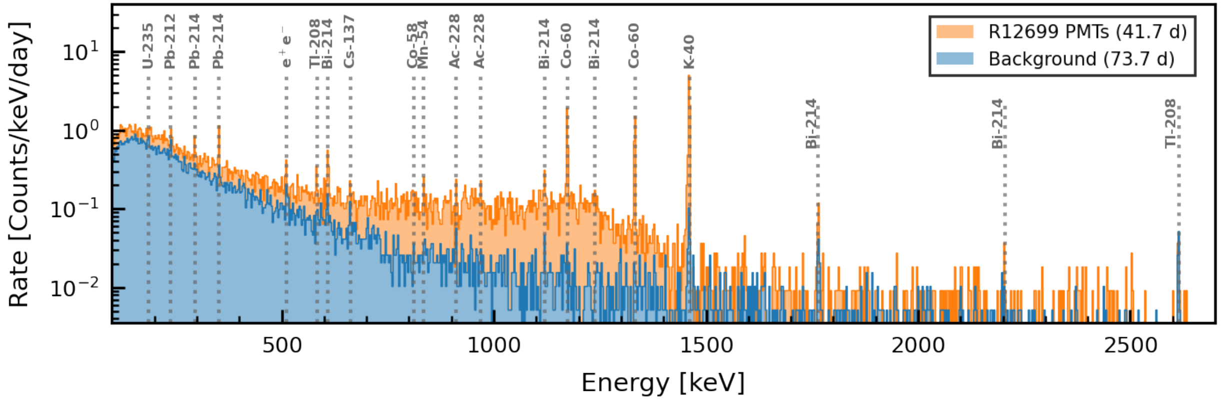
Sample Simulation and Analysis

- Calculation of the specific activities *A* from the background- and Compton-subtracted counts S_{net} at the location (±3σ) of the most prominent lines as

$$A = \frac{S_{net}}{r \cdot \varepsilon \cdot m \cdot t}$$

(branching ratio *r*, sample mass *m*, measuring time *t*)

- Combination to activities of isotopes / subchains (L_d @ 90% C.L.)



$$S_{net} = S - B \cdot \frac{t_S}{t_B} - B_C$$

$$L_d = k^2 + 2 \cdot L_c$$
$$L_c = k \cdot \sigma_{net}$$

[6]

[6] Anal. Chem. 1968, 40, 3, 586–593

Example: Hamamatsu PMT R12699-406-M4

For isotopes where detection limit is exceeded, current PMT model (still being optimized) has, per active photocathode area*,

- tenth – fourfold activities w.r.t. R11410 units (in XENON1/nT) [1]
- lower activity compared to the R8520 PMTs (in XENON100) [5]

➔ Good potential for future improvements through material selection for use in DARWIN

* R12699 ~ 23.5 cm², R11410 ~ 32.2 cm², R8520 ~ 4.2 cm²

Isotope	Confinement full PMT: Improved LRI model	Confinement full PMT: Initial model	Confinement full PMT: Prototype Screening 2018	Hamamatsu R11410	Hamamatsu R8520-06
	Detected/Limit (90 % C.L.) Activity [mBq/PMT]				
^{238}U	**< 6.92**	< 6.11	< 8.13	8 ± 2	< 15
^{226}Ra	**0.54 ± 0.09**	0.60 ± 0.10	0.54 ± 0.21	0.6 ± 0.1	< 0.28
^{228}Ra	**< 0.55**	< 0.65	< 0.95	0.7 ± 0.2	< 0.59
^{228}Th	**< 0.36**	< 0.53	0.49 ± 0.2	0.6 ± 0.1	0.3 ± 0.1
^{235}U	**< 0.32 [< 6.43]**	< 0.28 [< 5.66]	< 0.37 [< 9.51]	0.37 ± 0.09	< 0.67
^{60}Co	**0.08 ± 0.04**	1.31 ± 0.11	2.02 ± 0.19	0.84 ± 0.09	0.60 ± 0.04
^{40}K	**34.2 ± 3.6**	34.6 ± 3.7	26.3 ± 3.2	12 ± 2	12.0 ± 0.8
^{137}Cs	**< 0.113**	< 0.119	0.151 ± 0.058	–	< 0.1
^{54}Mn	**0.17 ± 0.04**	< 0.146	< 0.189	–	–
^{58}Co	**0.24 ± 0.04**	< 0.122	< 0.222	–	–
	Detected/Limit (90 % C.L.) Activity [mBq/cm^2]				
^{238}U	**< 0.294**	< 0.260	< 0.346	0.25 ± 0.06	< 3.569
^{226}Ra	**0.023 ± 0.004**	0.026 ± 0.004	0.023 ± 0.009	0.019 ± 0.003	< 0.067
^{228}Ra	**< 0.023**	< 0.028	< 0.040	0.022 ± 0.006	< 0.140
^{228}Th	**< 0.015**	< 0.023	0.021 ± 0.009	0.019 ± 0.003	0.071 ± 0.017
^{235}U	**< 0.014 [< 0.273]**	< 0.012 [< 0.241]	< 0.016 [< 0.404]	0.012 ± 0.003	< 0.159
^{60}Co	**0.0036 ± 0.0016**	0.055 ± 0.005	0.086 ± 0.008	0.026 ± 0.003	0.144 ± 0.010
^{40}K	**1.45 ± 0.15**	1.47 ± 0.16	1.12 ± 0.14	0.37 ± 0.06	2.86 ± 0.18
^{137}Cs	**< 0.005**	< 0.005	0.006 ± 0.002	–	< 0.024
^{54}Mn	**0.0070 ± 0.0015**	< 0.006	< 0.008	–	–
^{58}Co	**0.0103 ± 0.0018**	< 0.005	< 0.009	–	–

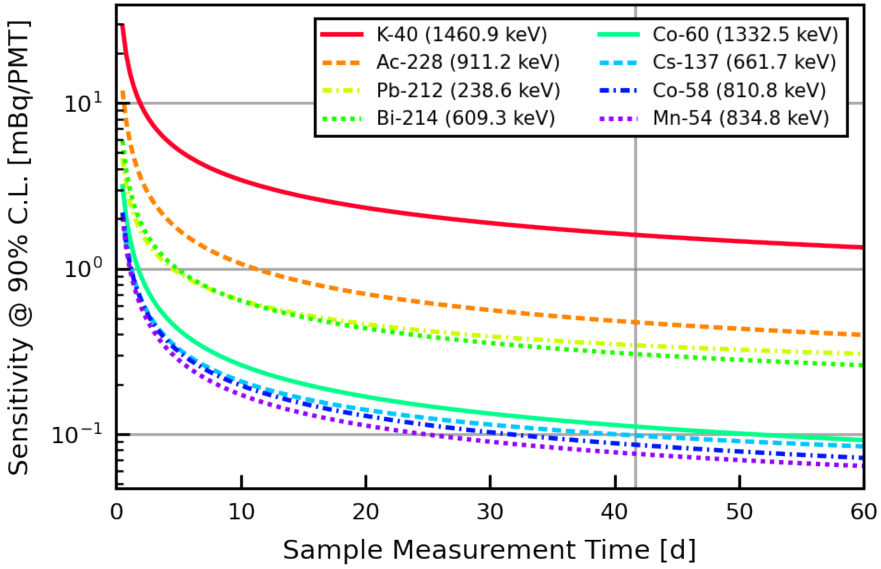
[1] Eur. Phys. J. C77 (2017) 890; [7] Astropart. Phys. 35 (2011) 43–49

Sample Simulation and Analysis

- Isotopes / chains of interest:
  - primordial: ^{238}U, ^{232}Th, ^{40}K
  - cosmogenic: ^{54}Mn, ^{46}Sc, ^{60}Co,…
  - anthropogenic: ^{137}Cs, ^{110m}Ag,…

  ➔ decay products may mimic signals or leak into the signal region

- Typical sensitivities: < a few mBq/kg for exposures of 1-3 weeks and several kg sample mass (a few µBq/kg for radio-pure samples, longer exposure and higher mass)



2 Hamamatsu R12699-406-M4 PMTs

Comparison to Other HPGe Spectrometers

Detector	Location (Depth m.w.e.)	Mass [kg]	Efficiency [%]	FWHM [keV]	Rate 60-2700 keV [cnts/(kg·day)]	Ref.
Gator	LNGS (3600)	2.2	100.5	1.98	89.0 ± 0.7	[2]
Maeve	SURF (4300)	2.0	85	3.19	956.1	[3]
GeMPI 3	LNGS (3600)	2.2	98.7	2.20	24 ± 1	[8]
Belmont	Boulby (2805)	3.2	160	1.92	135.0	[3]
GeOroel	LSC (2450)	2.3	109	1.85	165.3	[4]
GeMSE	LVdA (620)	2.0	107.7	1.96	88 ± 1	[9]

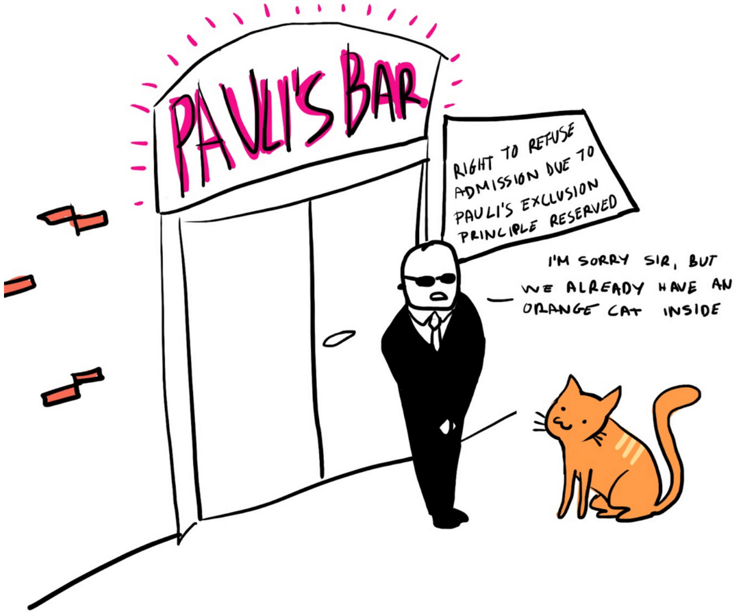
[2] JINST 17 (2022) P08010
[3] Eur. Phys. J. C80 (2020) 1044
[4] Bandac, “Ultra-Low Background Services in the LSC”, DS-Mat Meeting, GSSI, 2019
[8] N. Ackermann, private communication
[9] JINST 17 (2022) P04005

Tests of the Pauli-Exclusion-Principle (PEP)

- Two or more identical fermions cannot occupy the same quantum state within a quantum system simultaneously
- **Messiah–Greenberg Superselection Rule**

  The symmetry of the wave function of a steady state is constant in time

  ➔ the symmetry of a quantum state can only change if a particle, which is new to the system, interacts with the state
- Categorize PEP violation experiments by the “novelty” of the fermion-system interaction

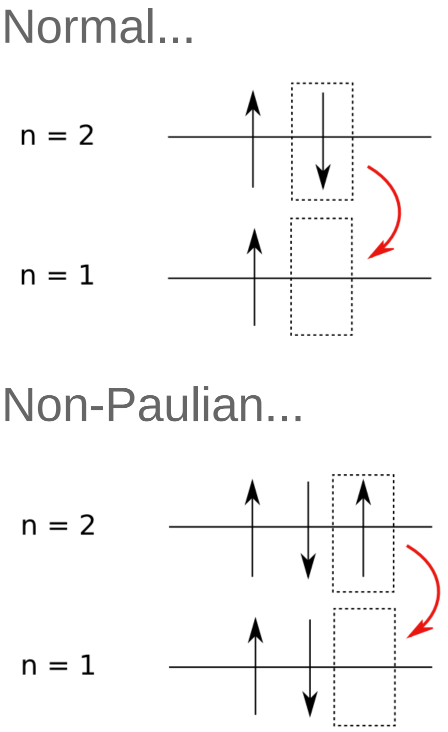


Ramberg-Snow Technique

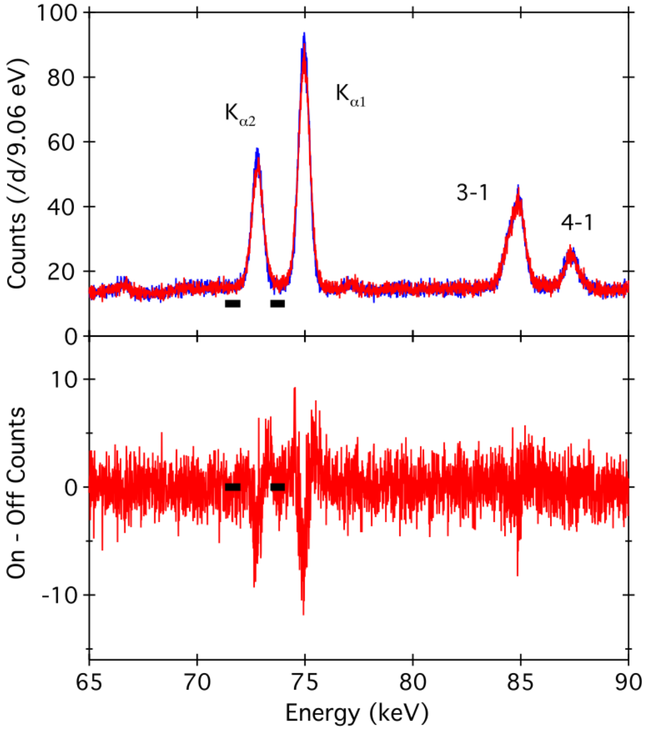
- Search for PEP forbidden atomic transitions
- Type II: electrons from external current

  ➔ fermion has not previously interacted with the investigated system
- Here: current through Pb

  ➔ e.g., 1s–2p$_{3/2}$ K$_{\alpha 1}$: 74.961 keV (allowed) / 73.713 keV (forbidden)



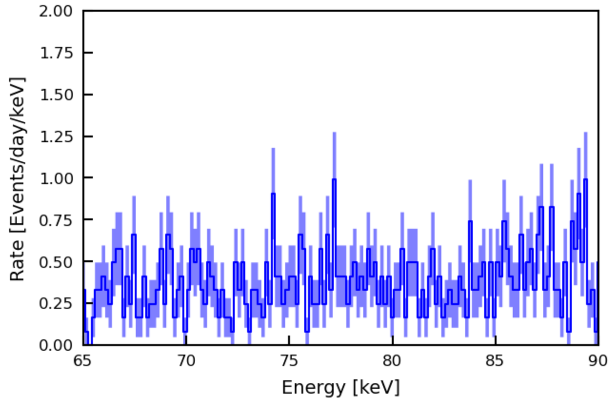
atomic 2p – 1s transition

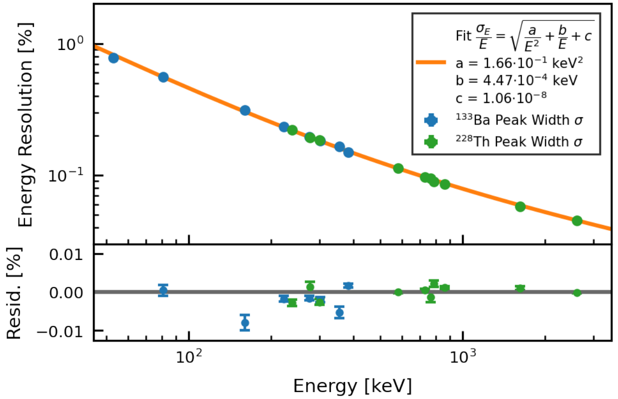


[10] Found Phys 42, 1015–1030 (2012)

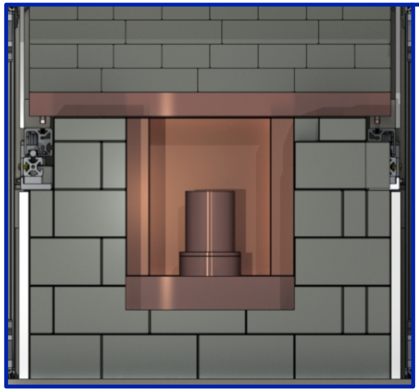
PEP Studies in Gator

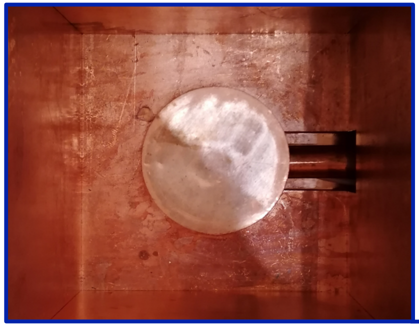
- Integrated background rate in the ROI (65-90 keV): (4.4±0.3) $d^{-1}kg^{-1}$
- Resolution (FWHM) at 74.96 keV: ~ 1.05 keV
- Low activity material selection based on previous screenings or new measurements on demand
  - Roman Pb sheets from Lemer Pax with <0.2 Bq/kg
  - OFHC copper and PTFE for support from XENON experiments
  - High current cables currently being screened
- Aim for currents up to 180 A (first step: 100 A)

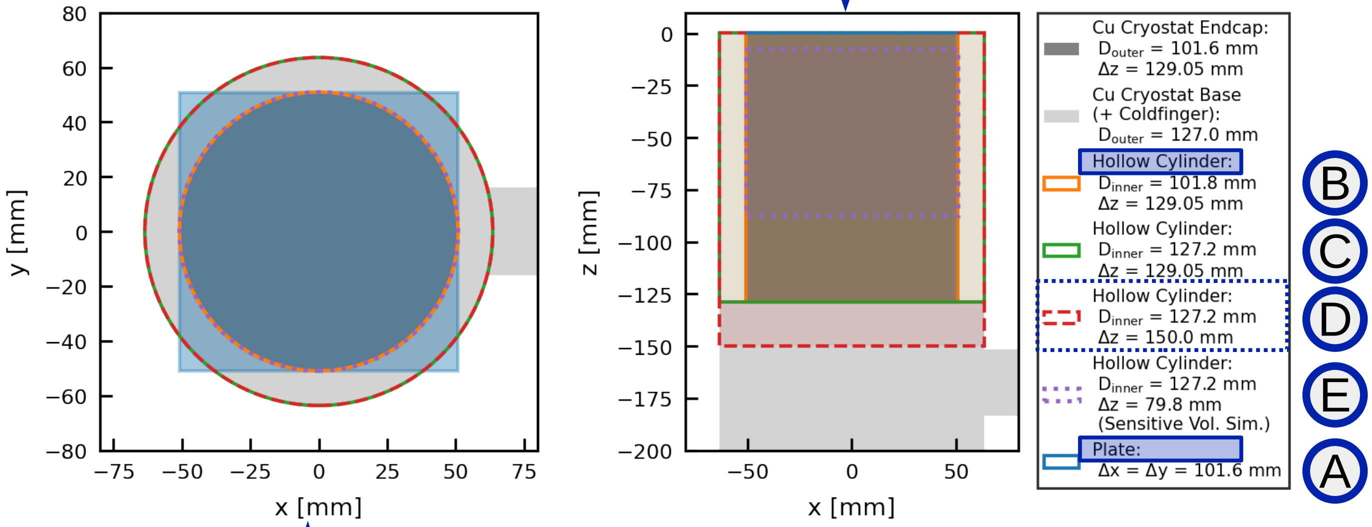




Simulations – Investigated Geometries Pb Conductor

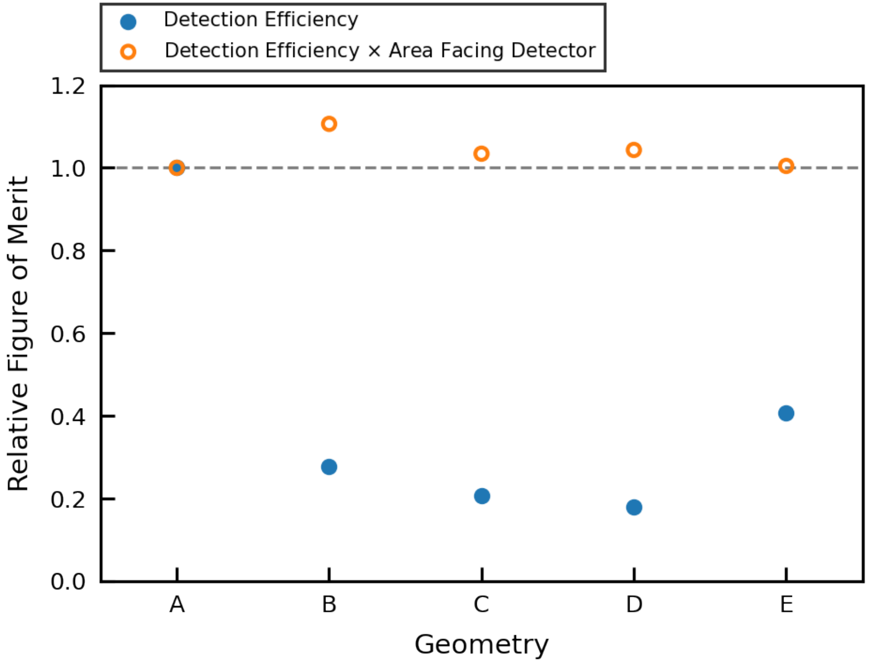




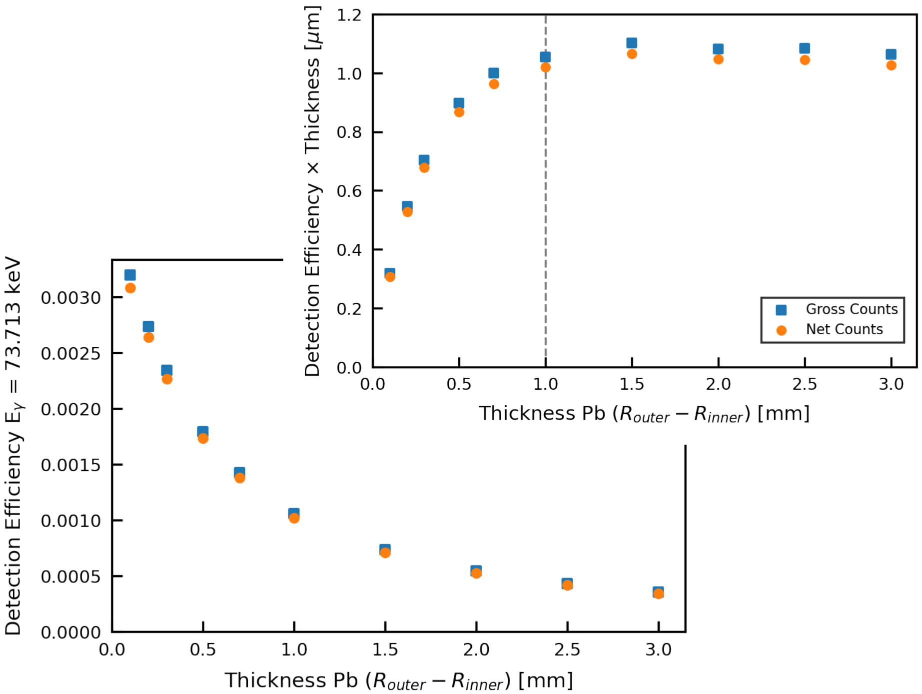


Detection Efficiency

Geometries

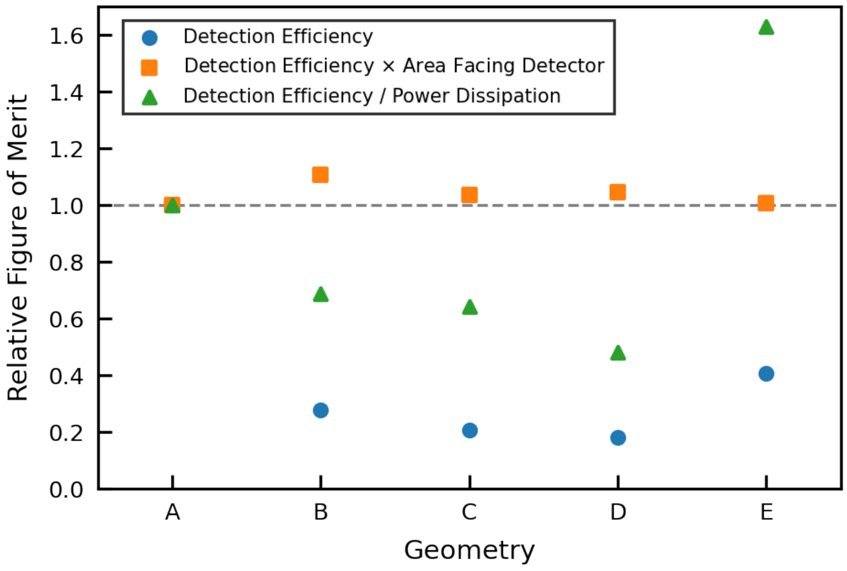


Thickness (Geom. D)

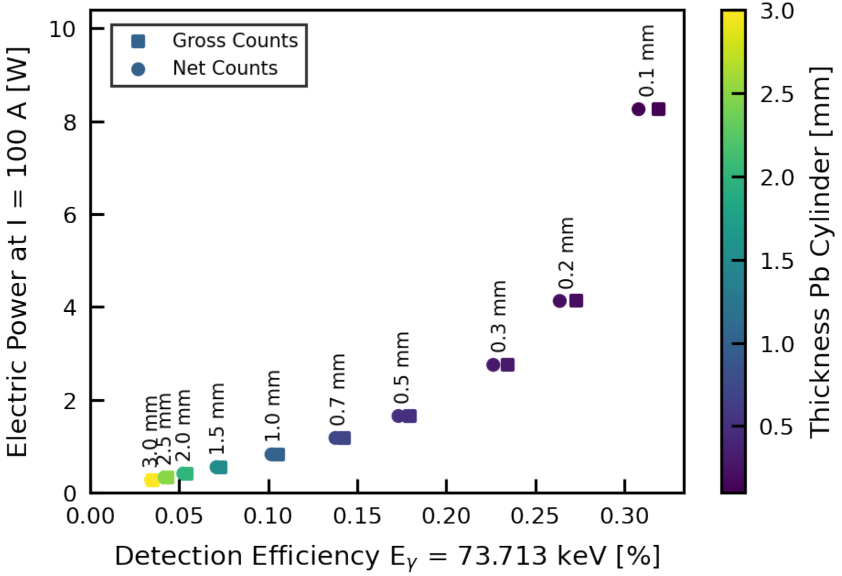


Power Dissipation

Geometries

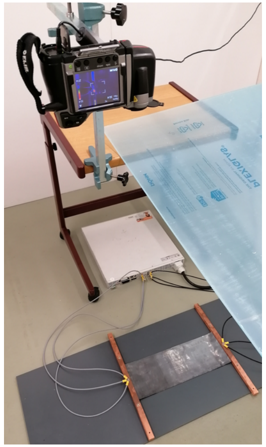


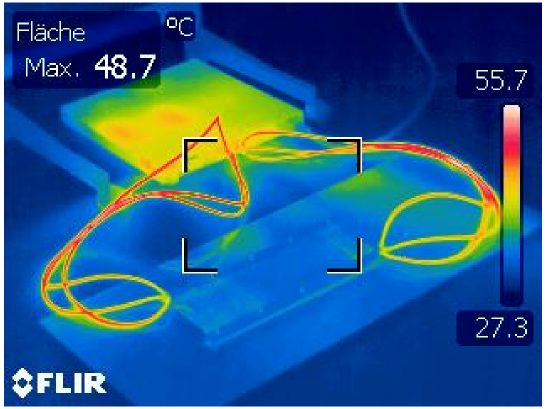
Thickness (Geom. D)

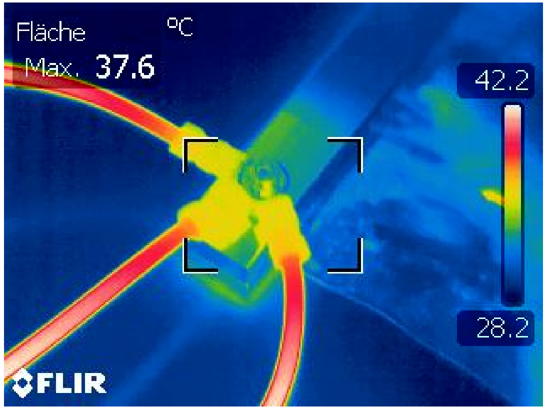


Heat-Up Tests

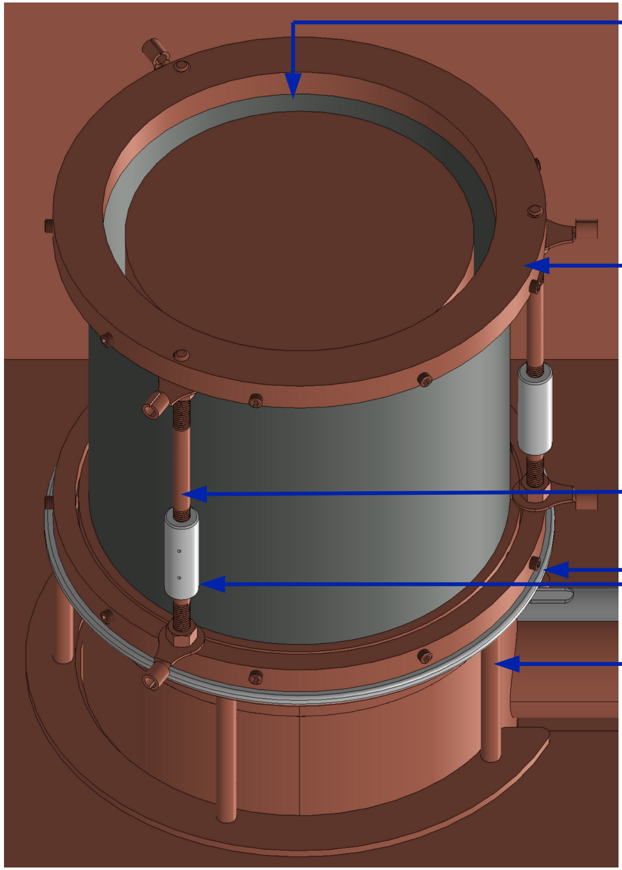
- Heat dissipation tests with flat geometry in 2 configurations for $42\times14.7\times0.05$ cm^3 Pb sheet (estimate 1.4 / 12.1 W Pb only)
- Currents up to 100 A, clamped in Cu bars ($\varnothing$ 2×1.6 cm^2, $\rho_{Cu} \approx 0.08\ \rho_{Pb}$), 27-28°C ambient temperature
- Significant heat-up of 3×4 mm^2 cables (estimate 32 W, resulting in increased R), Pb sheet / Cu bars mostly unaffected

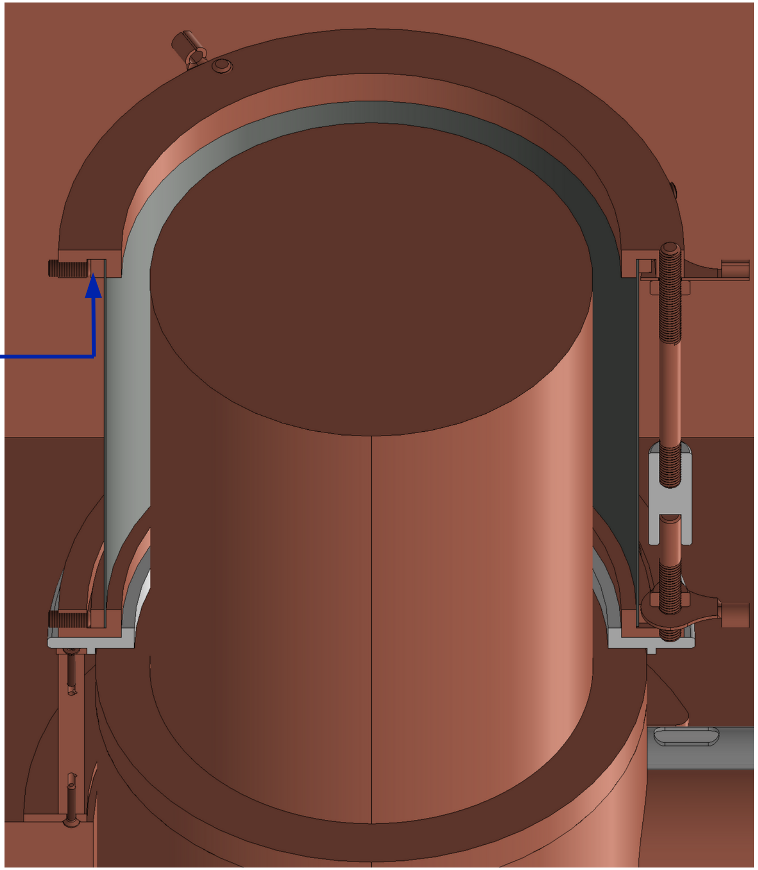






Setup Design

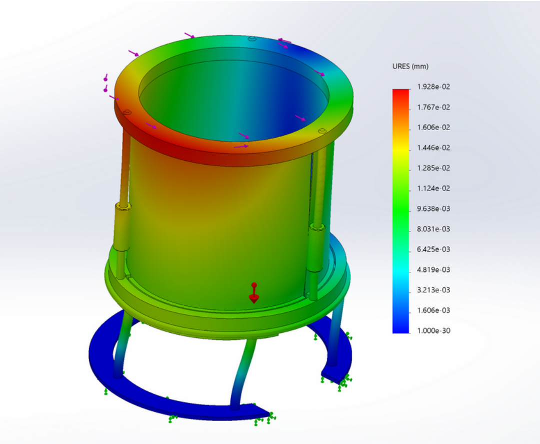


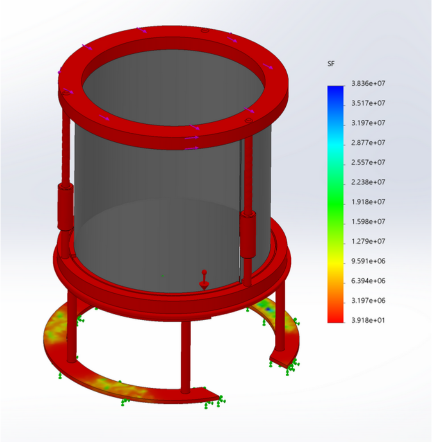


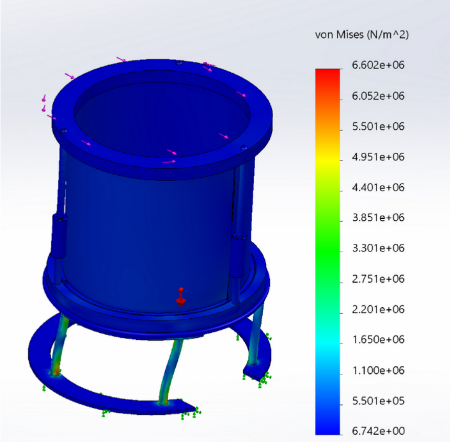
Trade-off low activity
(~mass, total ca. 1.5 kg)
⬌ low R & high stability

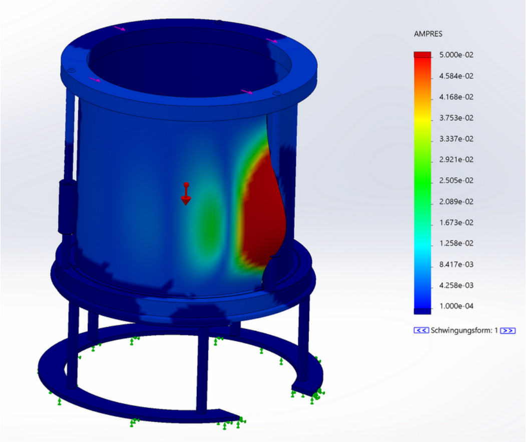
Stability Simulations

- SolidWorks stability simulations: static (stress, displacement, strain, safety factor) + buckling
- Gravity + different force / torque scenarios (shown: extreme case, i.e. gravity + 10 N lateral force top + 1 Nm torque)
- Minimum safety factor:
  - 570 (gravity only)
  - 39 (extreme case)



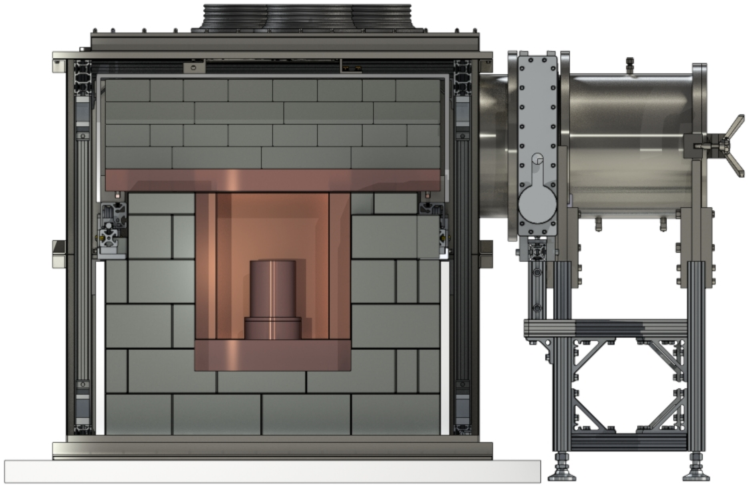


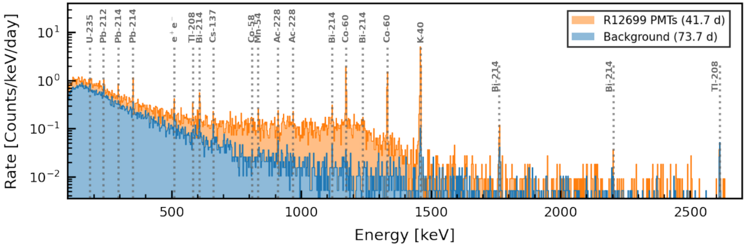




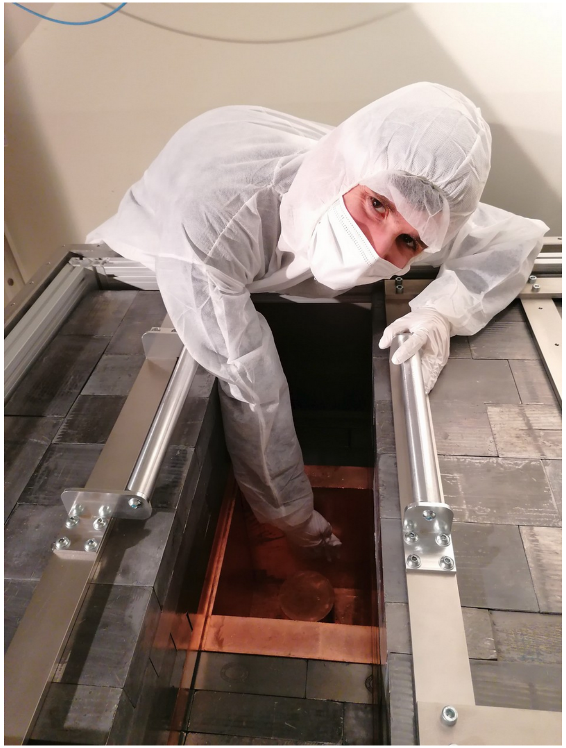
Summary and Outlook

- Low-background germanium counting facility Gator for high-sensitivity gamma-ray spectrometry
- Integrated background rate (100-2700 keV) of (82.0±0.7) $d^{-1}kg^{-1}$ comparable to world's most sensitive HPGe detectors
- Prospective material screenings for LEGEND-1000, DARWIN,…
- Search for Pauli-Exlusion-Principle forbidden atomic transitions in lead



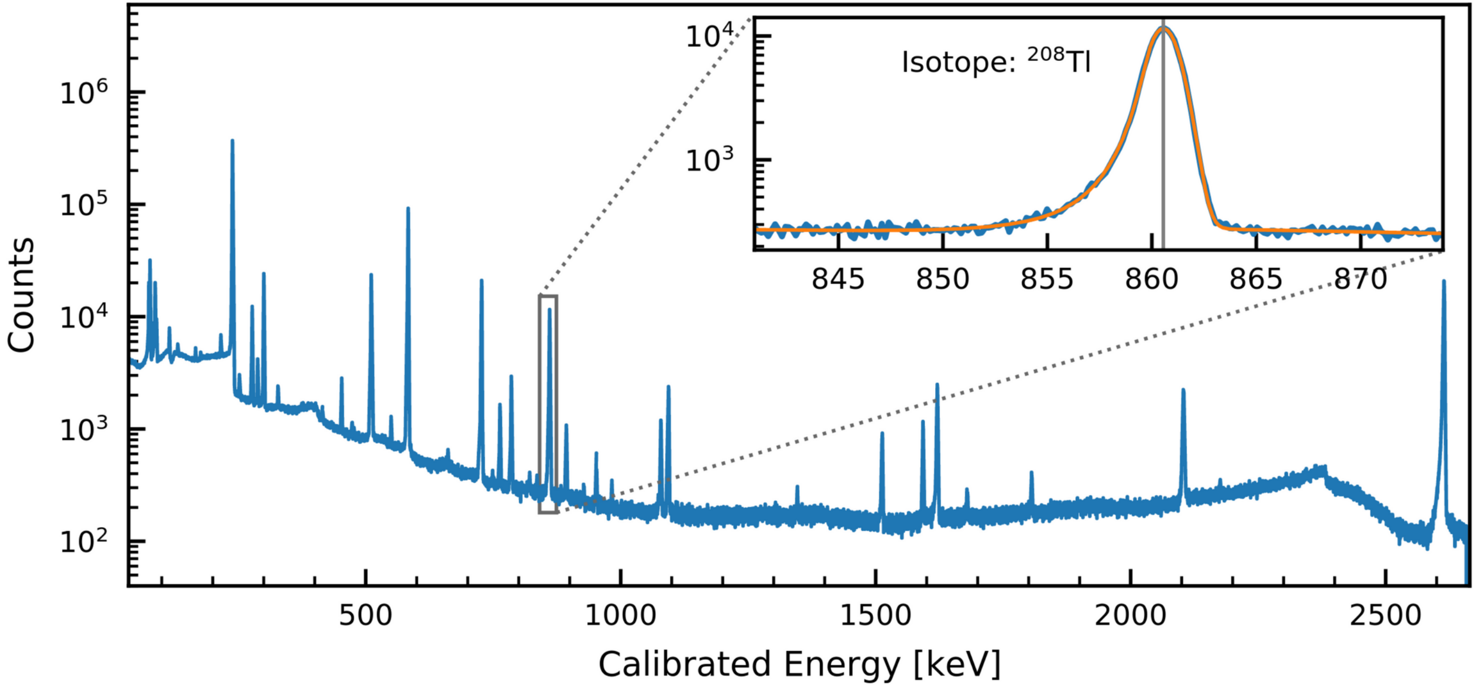


Thank you for your attention! Questions?



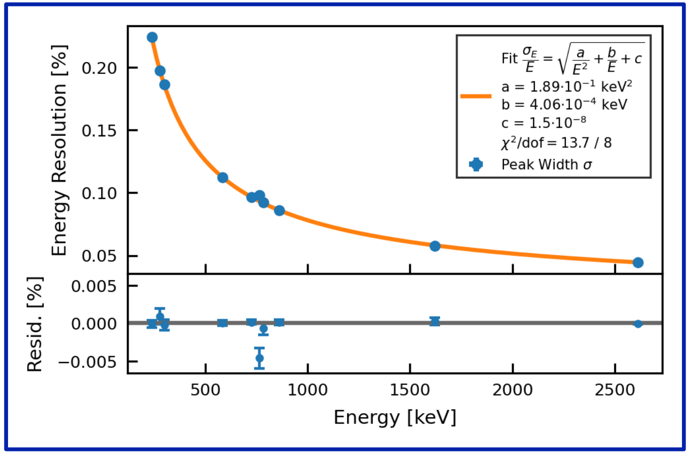
Appendix

Calibration Example: Th-228

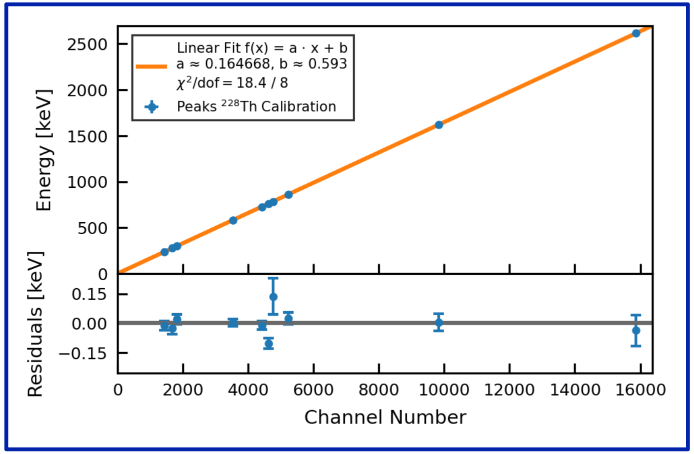


Calibration Example: Th-228

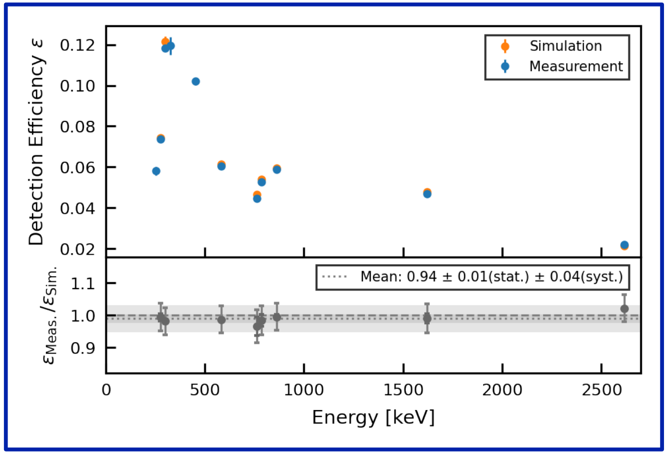
Energy resolution



Linearity

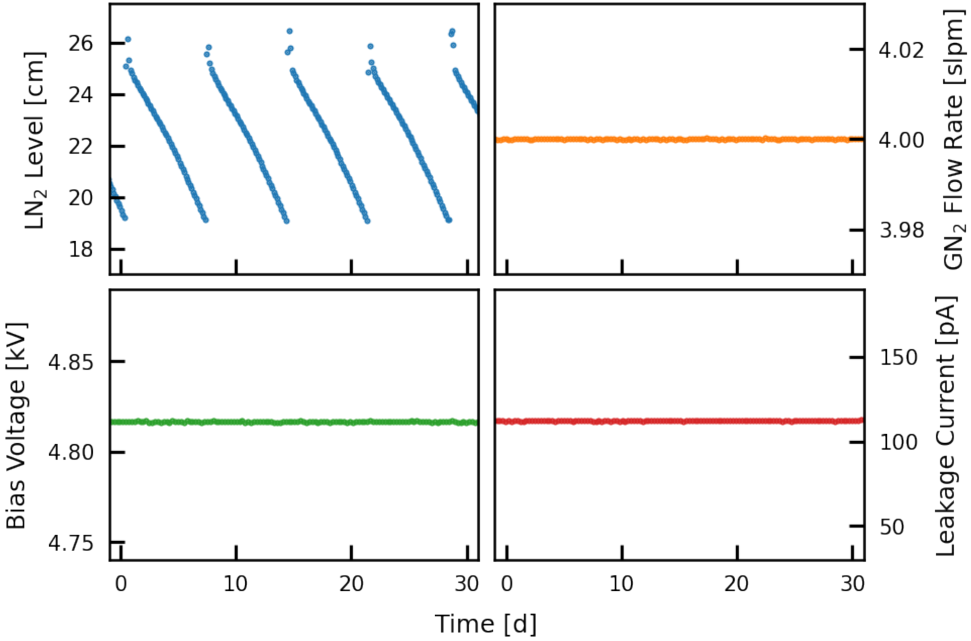


Verification Sim. Det. Efficiency



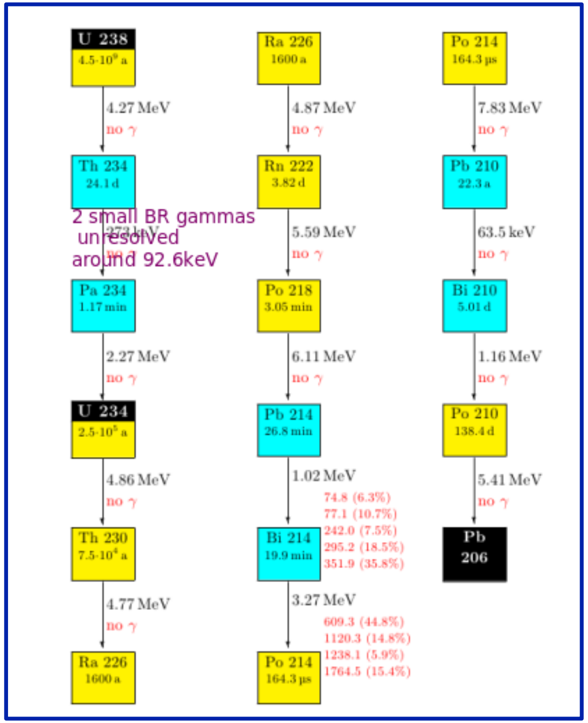
Monitoring Operations Parameters

- Remote monitoring (incl. alarms) of operations parameters to ensure detector stability and data quality
  - Trigger rate 100-2700 keV
  - Dewar LN_2 level ➔ weekly refills
  - GN_2 purge gas flow (4 slpm)
  - Bias voltage (4817±3) V
    ➔ Energy ROI in MCA range
  - Leakage current
  - Room temperature & pressure



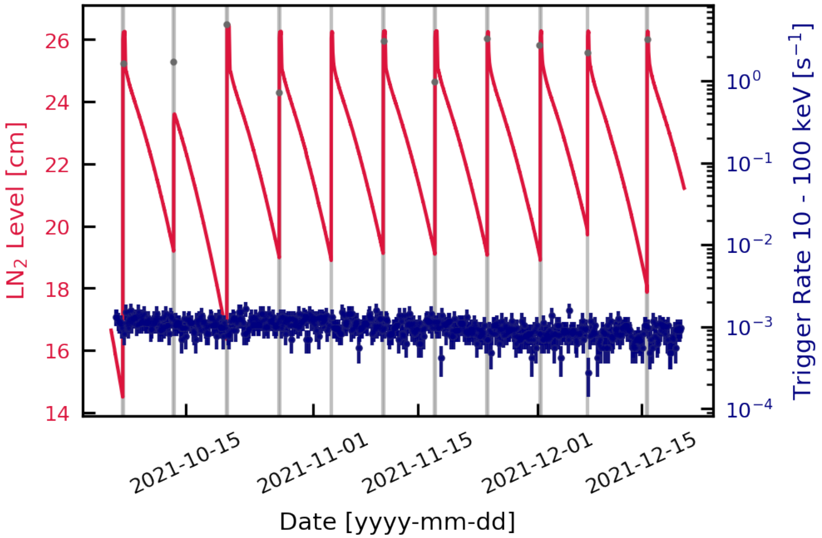
Background Contributions

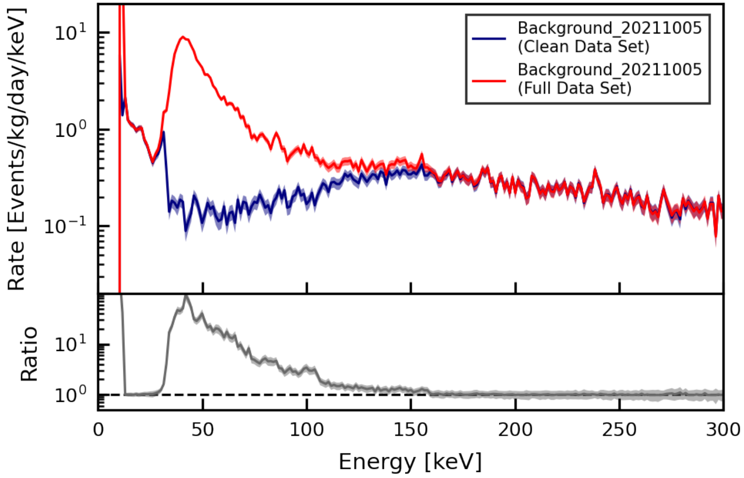
- Low E (< 100 keV): electronic noise
- Higher E: detector & shielding materials, environmental radon
  - ^{238}U, ^{232}Th and ^{235}U found naturally in minerals, daughters from α/β-decays detected in whole detector range
  - Gaseous ^{222}Rn from ^{238}U chain from rock / water
    ➔ ventilation, enclosure, GN_2 purge
    ➔ traced via ^{214}Bi decays
  - ^{40}K (present in Earth mantle)
  - Cosmogenic ^{60}Co (in Cu shield and enclosure)
  - Anthropogenic ^{137}Cs



Reproducible Low-Energetic Noise

- Observed low-energetic noise, temporally correlated with LN_2 dewar refills, that might leak into the ROI (contributes for energies of up to ~ 150 keV)
- Unbiased removal of affected data sets based only on derivative of LN_2 level





The Pauli-Exclusion-Principle (PEP)

Wolfgang Pauli

- Two or more identical fermions cannot occupy the same quantum state within a quantum system simultaneously
- Example: *(n, l, m_l, m_s)* for electrons in atoms
- Concerning the exchange of two identical particles, the total wave function is antisymmetric (symmetric) for fermions (bosons) ➔ different statistics

The *New* Electron Conundrum

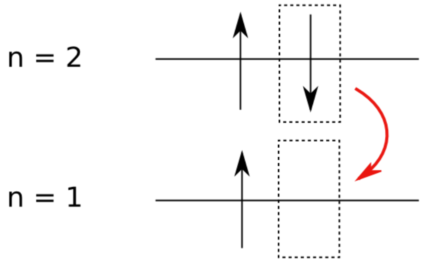
- Categorize experiments by how “new” the fermion-system interaction can be assumed to be
  - **Type I**: fermion has not previously interacted with any other fermions
    - primordial system formation
    - recently created fermions e.g. from β decay or pair production (Type Ia)
  - **Type II**: fermion has not previously interacted with that investigated system
    - distant fermions brought to interact with system e.g. Ramberg-Snow technique
    - nearby fermions brought to interact with system e.g. electrons in the Fermi sea of a conductor (Type IIa)
  - **Type III**: fermion within investigated system
    - violate the Messiah-Greenberg superselection rule

The *New* Electron Conundrum

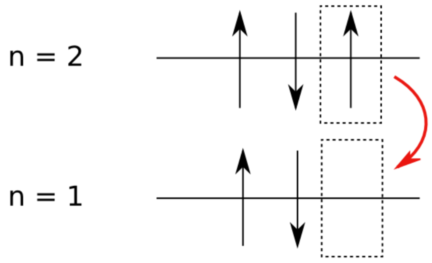
Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit	Reference
Atomic transitions				
$\beta^- + \text{Pb} \rightarrow \check{\text{Pb}}$	Ia		3×10^{-2}	[23]
$e^-_{pp} + \text{Ge} \rightarrow \check{\text{Ge}}$	Ia		1.4×10^{-3}	This work
$e^-_I + \text{Cu} \rightarrow \check{\text{Cu}}$	II		1.7×10^{-26}	[48]
$e^-_I + \text{Cu} \rightarrow \check{\text{Cu}}$	II		4.5×10^{-28}	[8]
$e^-_I + \text{Cu} \rightarrow \check{\text{Cu}}$	II		6.0×10^{-29}	[9]
$e^-_I + \text{Pb} \rightarrow \check{\text{Pb}}$	II		1.5×10^{-27}	This work
$e^-_f + \text{Pb} \rightarrow \check{\text{Pb}}$	IIa		2.6×10^{-39}	This work
$\text{I} \rightarrow \check{\text{I}} + \text{X-ray}$	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}	[49]
$\text{I} \rightarrow \check{\text{I}} + \text{X-ray}$	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}	[13]
Nuclear transitions				
$^{12}\text{C} \rightarrow {}^{12}\tilde{\text{C}} + \gamma$	III	$\tau > 6 \times 10^{27}$ y	1.7×10^{-44}	[38]
$^{12}\text{C} \rightarrow {}^{12}\tilde{\text{C}} + \gamma$	III	$\tau > 4.2 \times 10^{24}$ y		[3]
$^{12}\text{C} \rightarrow {}^{12}\tilde{\text{C}} + \gamma$	III	$\tau > 5.0 \times 10^{31}$ y	2.2×10^{-57}	[11]
$^{16}\text{O} \rightarrow {}^{16}\tilde{\text{O}} + \gamma$	III	$\tau > 4.6 \times 10^{26}$ y	2.3×10^{-57}	[51]
$^{12}\text{C} \rightarrow {}^{12}\tilde{\text{N}} + \beta^- + \bar{\nu}_e$	IIIa	$\tau > 3.1 \times 10^{24}$ y		[3]
$^{12}\text{C} \rightarrow {}^{12}\tilde{\text{N}} + \beta^- + \bar{\nu}_e$	IIIa	$\tau > 3.1 \times 10^{30}$ y		[11]
$^{12}\text{C} \rightarrow {}^{12}\tilde{\text{N}} + \beta^- + \bar{\nu}_e$	IIIa	$\tau > 0.97 \times 10^{27}$ sec	6.5×10^{-34}	[35]
$^{12}\text{C} \rightarrow {}^{12}\tilde{\text{B}} + \beta^+ + \nu_e$	IIIa	$\tau > 2.6 \times 10^{24}$ y		[3]

Found Phys 42, 1015–1030 (2012)

Normal...



Non-Paulian...



atomic 2p – 1s transition

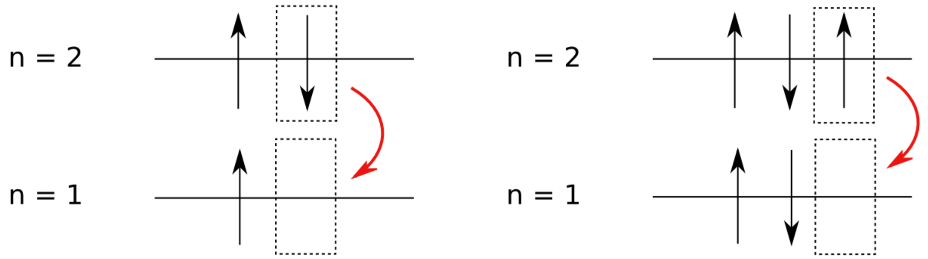
Atomic Theory

- Objective: capture of free electron onto atom via PEP violating process
- Capture probability:

$$\sigma_D = \sum_{n\geq 2} \frac{8\pi}{3\sqrt{3}} \frac{\alpha^5}{n^3} \frac{Z_{eff}^4}{K(K+E_n)}$$

➔ P_{cpt} = 0.009 (0.058) for Pb (Cu)

- Cascade
- X-ray energies:
➔ energy shifted down due to additional shielding of the nuclear charge



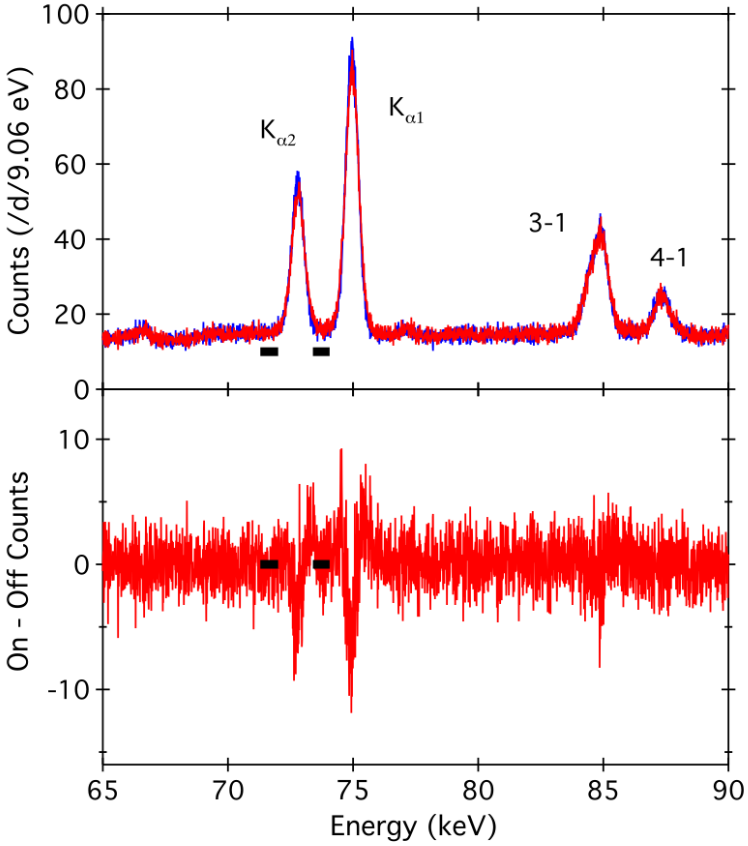
Transition	Cu		Ge		Pb	
	Forb.	Allow.	Forb.	Allow.	Forb.	Allow.
$1s$–$2p_{3/2}$ $K_{\alpha 1}$	7741	8047	9543	9886	73713	74961
$1s$–$2p_{1/2}$ $K_{\alpha 2}$	7723	8027	9516	9854	71652	72798
$2p_{3/2}$–$3s$	738		953		8920	
$2p_{1/2}$–$3d_{3/2}$	873	951	1131	1221	12241	12611
$2p_{3/2}$–$3d_{3/2}$	856	931	1104	1189	10180	10448
$2p_{1/2}$–$3s$	755		981		10981	
$2p_{3/2}$–$3d_{5/2}$	856	931	1104	1190	10276	10550

Found Phys 42, 1015–1030 (2012) Energies in eV

The Experiments – Current Through Lead

- Ramberg-Snow concept ➔ **Type II experiment**
- Compare current-on/-off data in regions with minimal sqrt(B)/ε_{ROI}
- Increased width and background in current-on weakens constraint on ½β^2
- Resulting 3σ upper limit:

$$\frac{1}{2}\beta^2 < \frac{N_{3\sigma}}{N_{new}\epsilon_x P_{cpt} N_{int}} = 1.5 \times 10^{-27}$$



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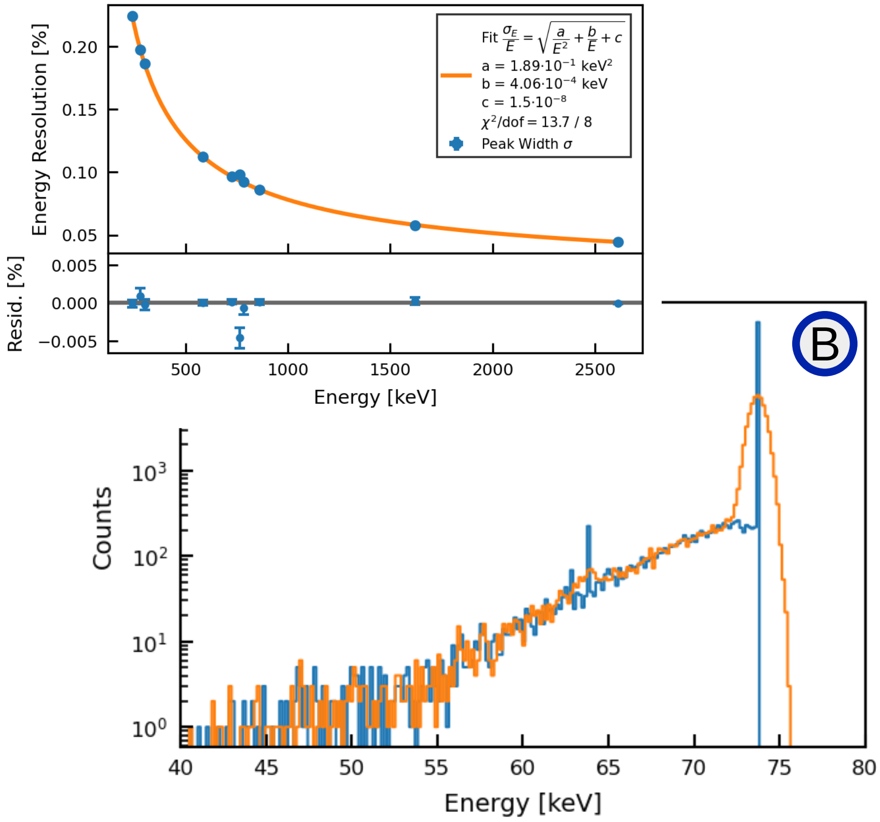
Geant4 Simulations

- Geant4 simulations with framework for sample efficiency simulations*
- Number of simulated gammas: 10^7 – 10^8 (depending on thickness)
- Gamma energy: 73.713 keV (energy of PEP violating Pb $K_{\alpha1}$)
- Reduced length (0.1 µm) and energy (250 eV) cuts in *PhysicsList*
- Energy-resolution smearing, binning according to Gator MCA



*https://github.com/Physik-Institut-UZH/Gator_2020

Electrical Connections

- Agilent 5761A high current supply (0-6V, 0-180A)
- High current DSUB (40 A/pin) connector in top plate
- Multiple cables for flexibility and heat dissipation
- Segmented OFHC Cu rod with PTFE insulation into sample chamber