Analysis of the light attenuation measurement in liquid argon in the GERDA cryostat

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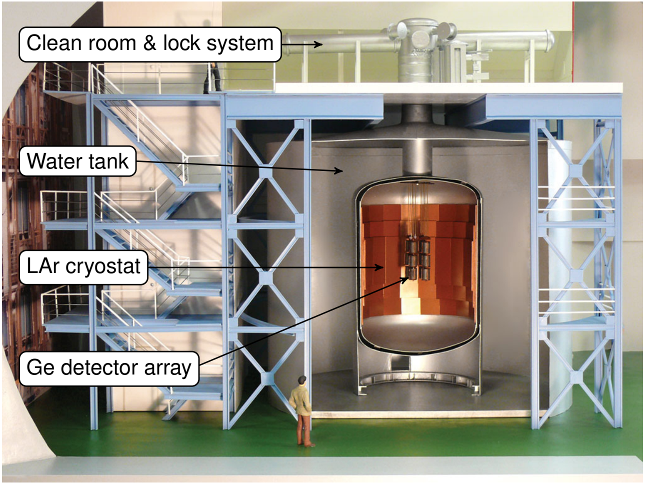
Outline

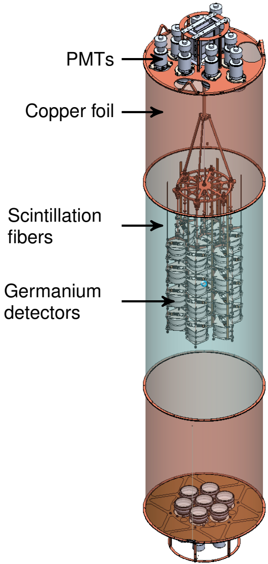
1. The GERDA experiment
2. Setup for the attenuation measurement
3. LAr scintillation mechanism
4. Simulation of the setup and analysis of the data
5. Results and conclusion

GERDA – **Ger**manium **D**etector **A**rray



- Search for $0\nu\beta\beta$ in ^{76}Ge
- Source = Detector
- LAr for cooling & shielding, scintillation veto
- Water used as muon veto & neutron shield
- Phase I: $21.6\,\mathrm{kg}\cdot\mathrm{yr}$, BI $10^{-2}\ \frac{\mathrm{cts}}{\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{yr}}$
- Goal Phase II: $100\ \mathrm{kg}\cdot\mathrm{yr}$, BI $10^{-3}\ \frac{\mathrm{cts}}{\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{yr}}$

LAr veto in Phase II



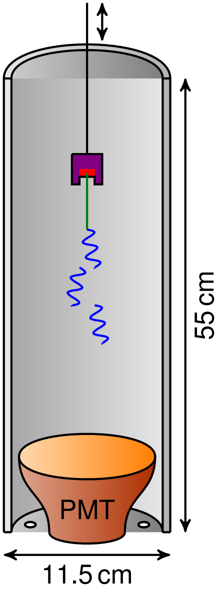
LAr veto

- $\beta\beta$-events do not trigger scintillation light
- Background events in the ROI typically have excess energy
  $\rightarrow$ deposited in the LAr
- Anti-coincidence veto on Ge-detectors suppresses background
- **Light attenuation is one of the most important parameters for the veto efficiency**

Light attenuation measurement

- Dedicated setup was developed
- Measurement performed in the LAr cryostat in GERDA during preparations for Phase II

Concept of the setup

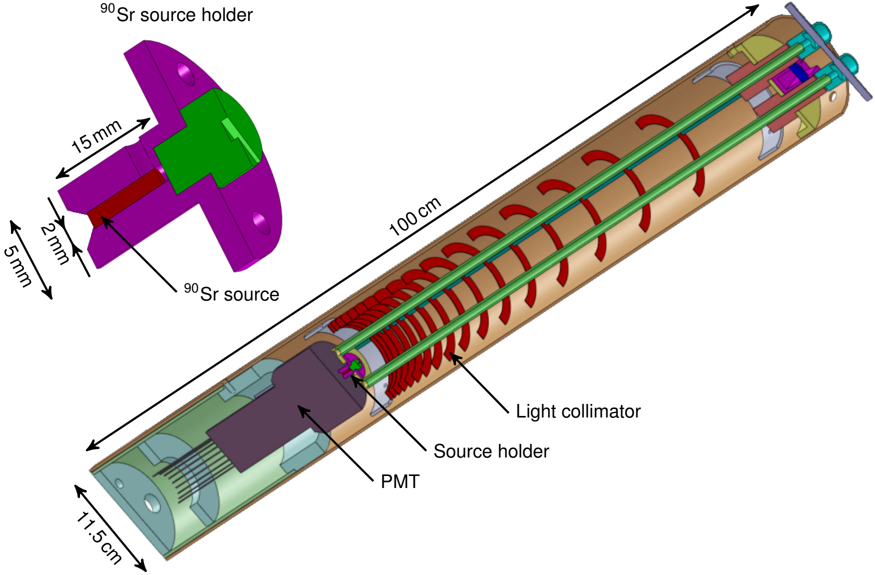


- Steel cylinder
- 3” PMT coated with WLS
  - → Model R11065 from Hamamatsu
- Encapsulated ^{90}Sr-source, pure β-emitter, to trigger scintillation light (128 nm)

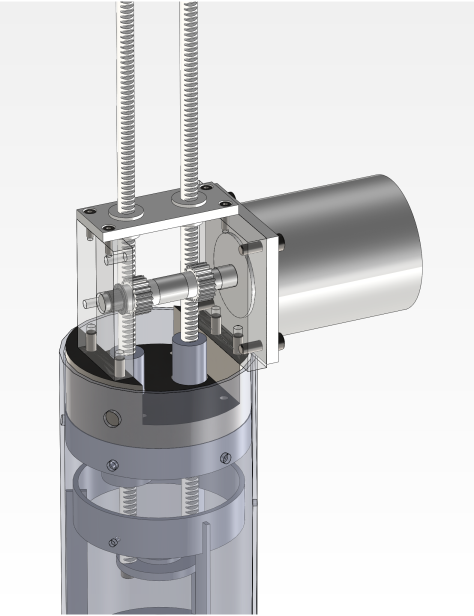
$$^{90}\mathrm{Sr} \xrightarrow[546\,\mathrm{keV}]{100\,\%\ \beta^-} {}^{90}\mathrm{Y} \xrightarrow[2280\,\mathrm{keV}]{100\,\%\ \beta^-} {}^{90}\mathrm{Zr}\ \text{(g.s. to g.s.)}$$

- Moveable source holder, made of steel
- Solid angle correction depends on distance between PMT and source
- Collimators to remove light reflection
  - → Reflectivity of steel is a huge uncertainty for the solid angle correction

Setup and source holder design

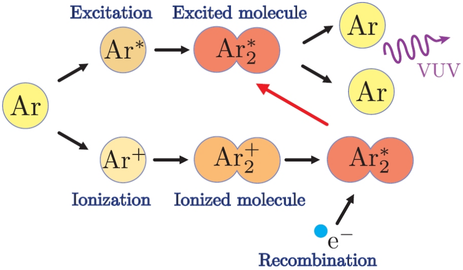


Stepping motor



- Motor VSS 57.200.2,5 from Phytron
- Designed for operation in cryogenic liquids

Argon scintillation mechanism



[arXiv:0708.2621v1]

- Ionizing radiation leads to excited or ionized argon atoms
  $\rightarrow$ Forming molecules with ground state argon atoms
- Ar_2^+ recombine with free electrons into excited states
- Excited states are created in:
  - singlets (allowed, $\tau \sim 4 - 7$ ns)
  - triplets (forbidden, $\tau \sim 1.0 - 1.7$ µs)
  - singlet to triplet production ratio is 0.3 for electrons

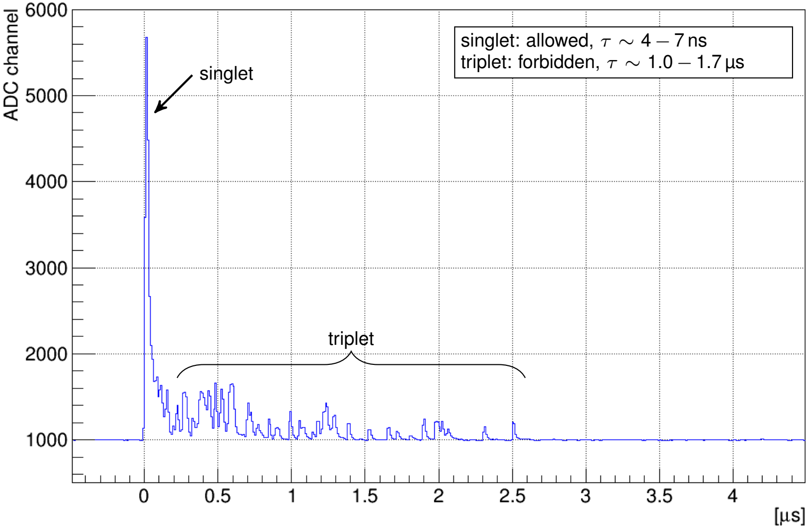
  $\rightarrow$ decay by emission of photons, $\lambda = 128$ nm
- Contaminations lead to reduction of triplet lifetime and extinction of scintillation light

Consequences of impurities in LAr

- $\mathbf{O_2}$: Free electrons are bound by Oxygen molecules $e^- + O_2 \rightarrow O_2^-$
  Non-radiative collision $Ar_2^* + O_2 \rightarrow 2Ar + O_2$
  Absorption of scintillation photons, emission of Oxygen resonance line at 557 nm
- $\mathbf{N_2}$: Non-radiative collision $Ar_2^* + N_2 \rightarrow 2Ar + N_2$
- $\mathbf{Xe}$: Emission of the Xenon resonance line around 149 nm,
  emission of Xenon excimer at 175 nm

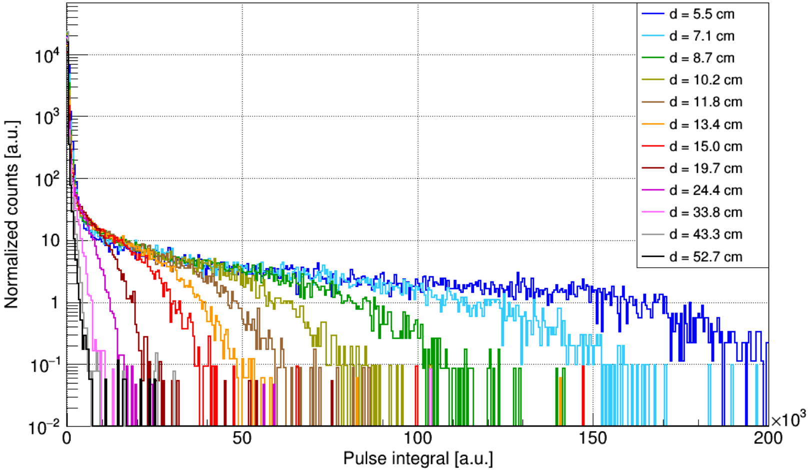
α_{att}	Impurity	concentration	Reference
50 cm	O_2, H_2O, CH_4	100 ppb	arXiv:1611.02481
	Xe, Kr	1 ppb	
	Hg	10 ppb	
	N_2	1 ppm	
110 cm	Xe	0.1 ppm	arXiv:1511.07725
66 ± 3 cm			interpreted as scattering
118 ± 10 cm	Xe	3%	NIMPRS A: V. 384, 380-386
1790 ± 160 (m?)	N_2	37 ppb	arXiv:1306.4605
30 ± 3 m	N_2	2 ppb	

Trace of a scintillation event



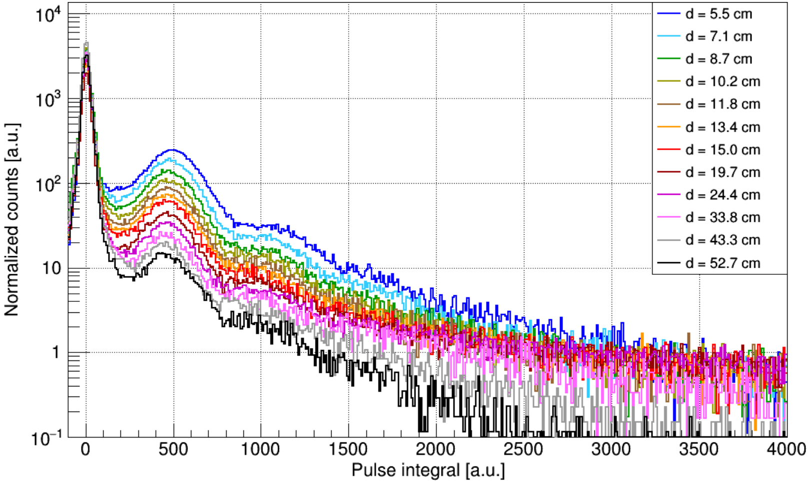
- Scintillation event composed of fast singlet and slow triplet component
- Obtain spectra by integrating the trace of each event

Pulse integral spectra



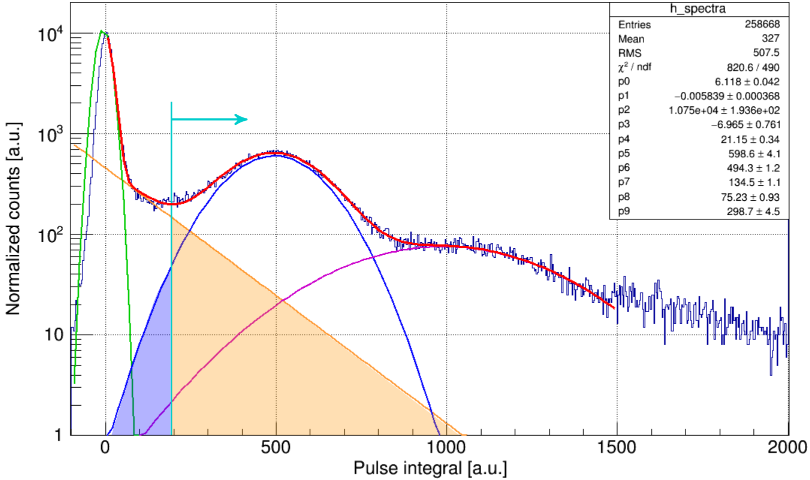
- Spectra for various distances, normalized on life time and ratio of accepted vs. found events

Spectra low energy region



- Peak-to-valley: $\sim$ 3:1
- Cut in valley between pedestal and single p.e. peak

Spectra low energy region



- $$f(x) = \underbrace{e^{p0+p1\cdot x} + p2\cdot e^{-\frac{(x-p3)^2}{2\cdot p4^2}}}_{\textbf{Pedestal}} + \underbrace{p5\cdot e^{-\frac{(x-p6)^2}{2\cdot p7^2}}}_{\textbf{single p.e. peak}} + \underbrace{p8\cdot e^{-\frac{(x-2\cdot p6)^2}{2\cdot p9^2}}}_{\textbf{double p.e. peak}}$$
- Integrate spectra at the right side of the cut in the valley
- Subtract exponential part of the pedestal, add gaussian part of the single p.e. peak

Sketch of the analysis

- Intensity of the scintillation light after distance d:

$$I(d) = I(d_0) \cdot \mathrm{e}^{-d/\alpha_{\text{att}}} \quad \text{with} \quad \frac{1}{\alpha_{\text{att}}} = \frac{1}{\alpha_{\text{abs}}} + \frac{1}{\alpha_{\text{scatt}}}$$

- $\alpha_{\text{att}} =$ attenuation length, distance where the intensity has dropped to 1/e $\approx$ 37%
- α_{scatt} at 128 nm about 70 cm
  [Rayleigh Scattering in Rare Gas Liquids: Seidel, Lanou, Yao; arXiv:hep-ex/0111054]
- Choose closest measuring point as reference:

$$\frac{I_i}{I_1} = \mathrm{e}^{-\Delta d/\alpha_{\text{att}}}$$

- Determine **solid angle correction** and **Cherenkov background** with simulation (MaGe, Geant4)
- Apply solid angle correction factor s_i to relative integrals: $\frac{I_i}{I_1} \longrightarrow \frac{s_i \cdot I_i}{s_1 \cdot I_1}$
- Plot the corrected relative integrals over relative distance Δd
- Fit function = signal + background

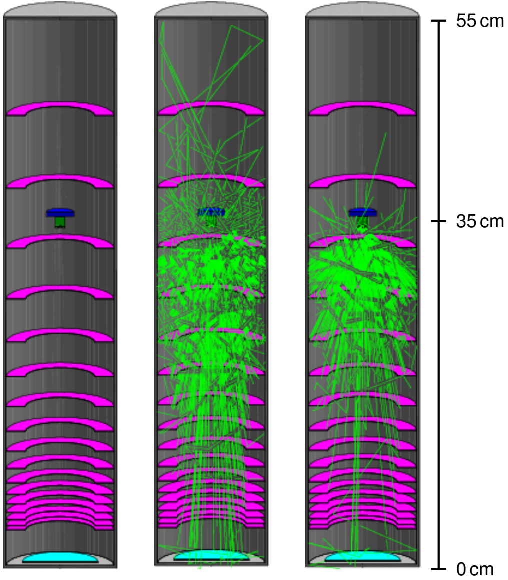
Solid angle correction with MC simulation

Effective distance

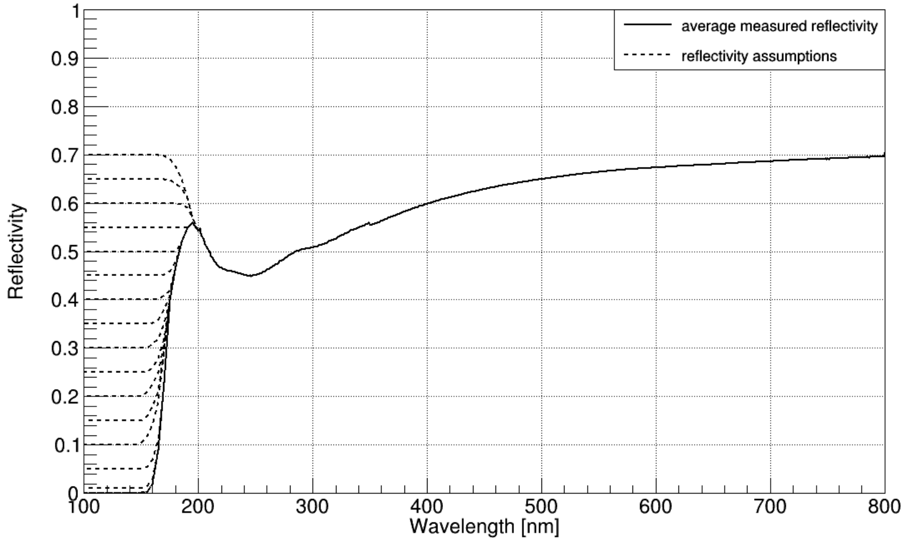
- Set α_{abs} very long (1 km)
- Determine average path a scintillation photon has traveled (before hitting WLS)
- Include reflected, Rayleigh scattered and scintillation photons as follow-up by bremsstrahlung
- **Don't** include Cherenkov light

Solid angle correction

- Consider all hits that are not produced by Cherenkov effect
- For $\alpha_{abs} = \infty$ the solid angle correction should yield the same signal strength for each distance

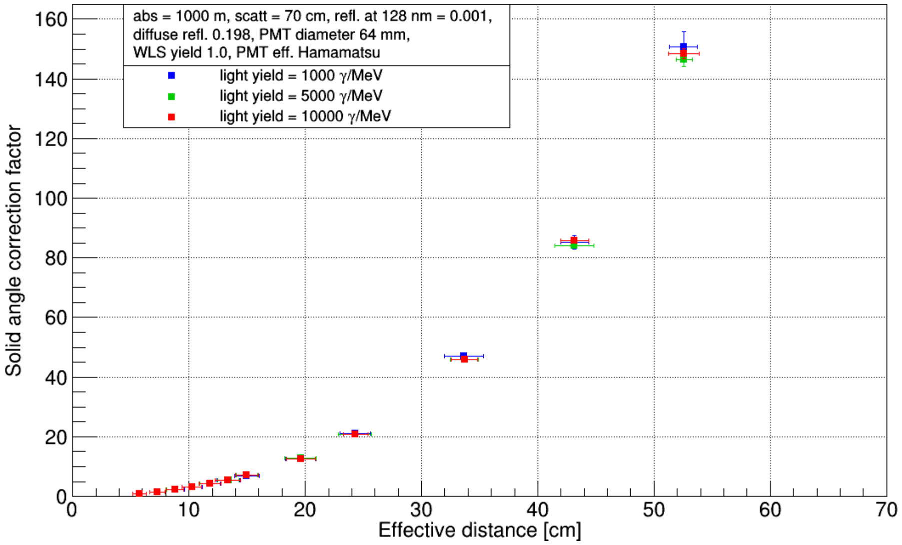


Reflectivity of steel for simulation



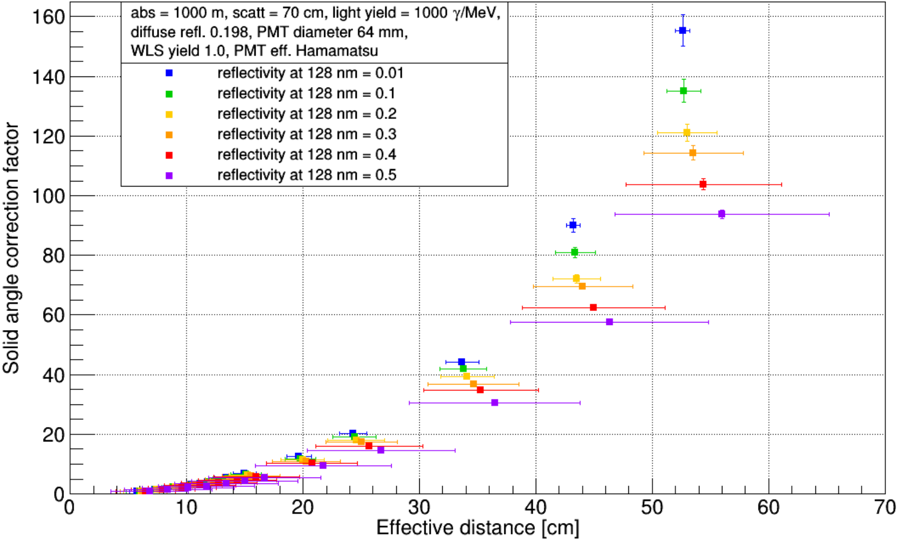
- Reflectivity of steel measured between 200 nm and 800 nm
- Reflectivity below 200 nm must be assumed for simulation

Solid angle correction is independent of LAr scintillation light yield:



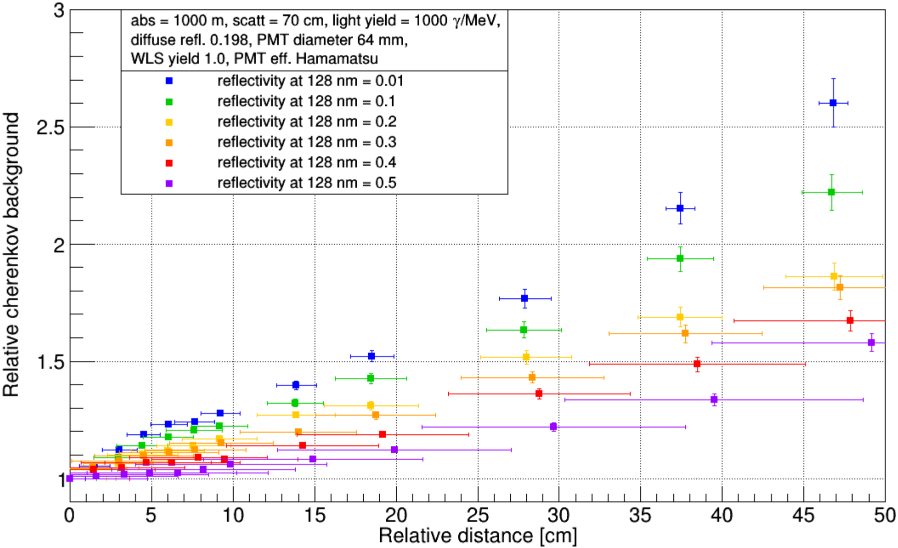
Resulting solid angle correction factors

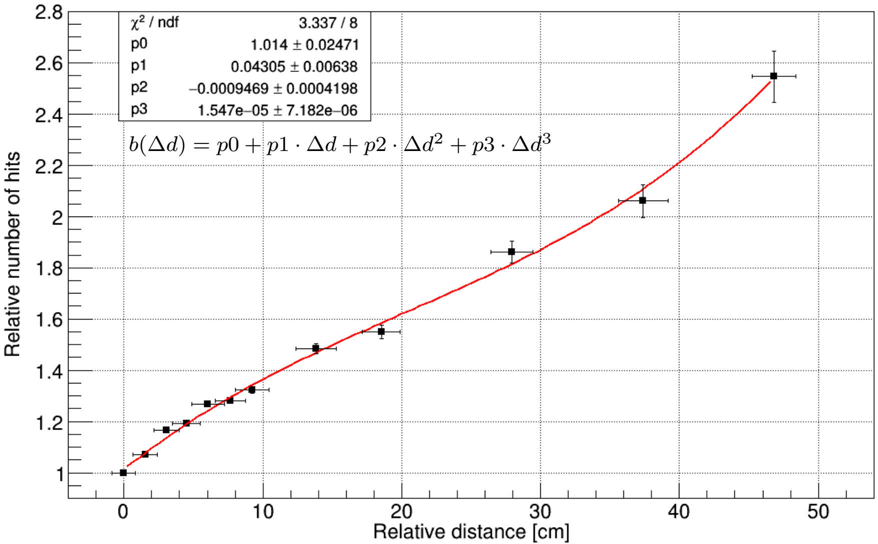
Solid angle correction is dependent on reflectvity of steel at 128 nm:



Cherenkov background

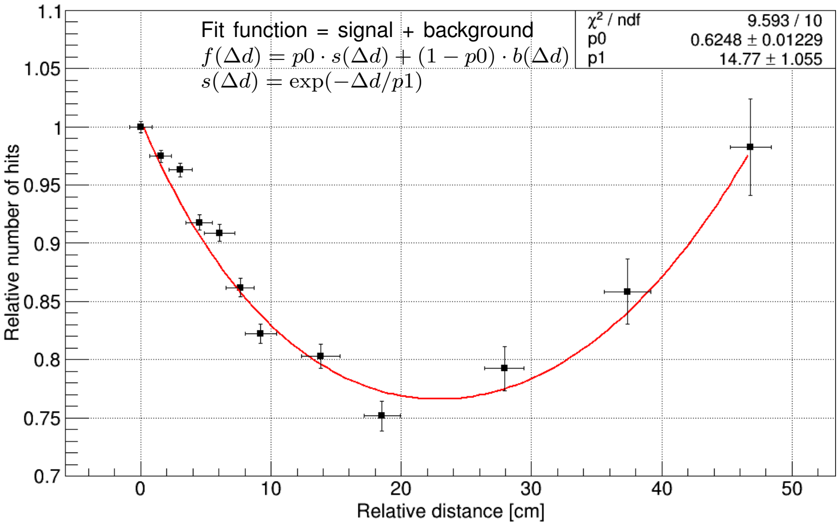
Find analytic description of the Cherenkov background for each reflectivity assumption:





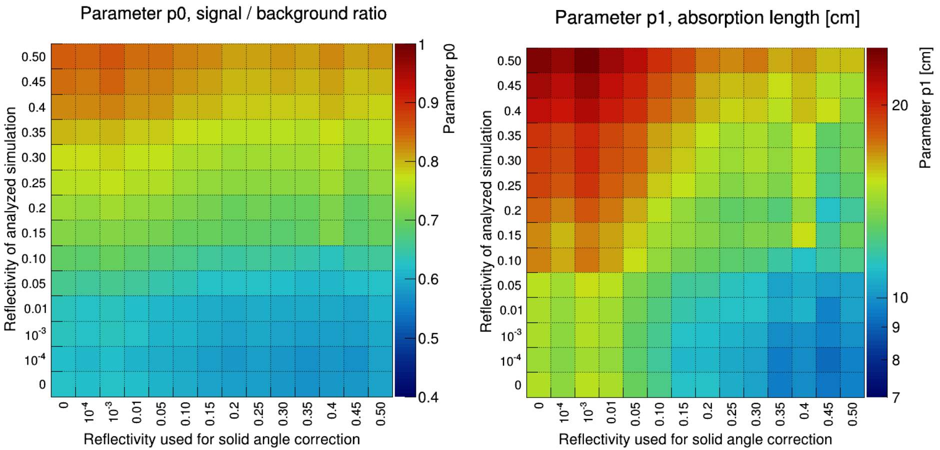
- Geometric effects within the setup lead to a non-constant background
- Consider this fit function as the background → add it to the fit of α_{abs}

Fit with solid angle correction and background



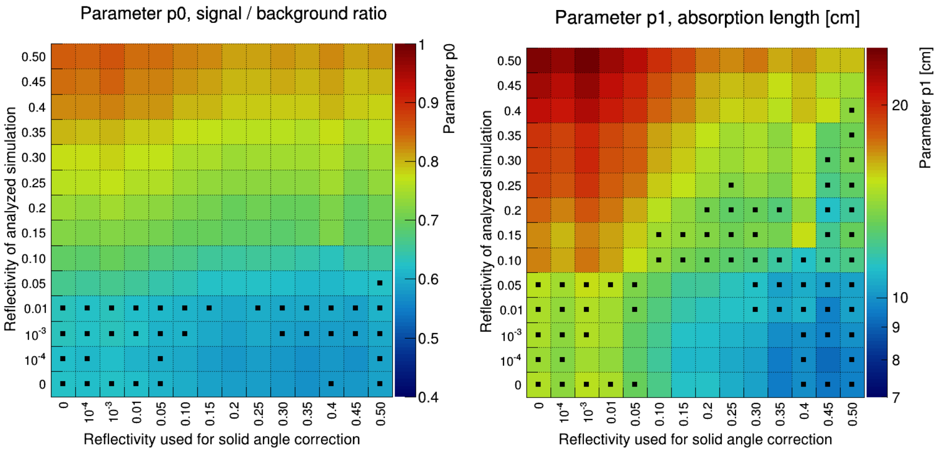
- $p0 \rightarrow$ ratio of signal vs. background, indication for light yield
- $p1 \rightarrow$ absorption length [cm]
- Find combination of simulation parameters which matches the data

Fit parameter investigation



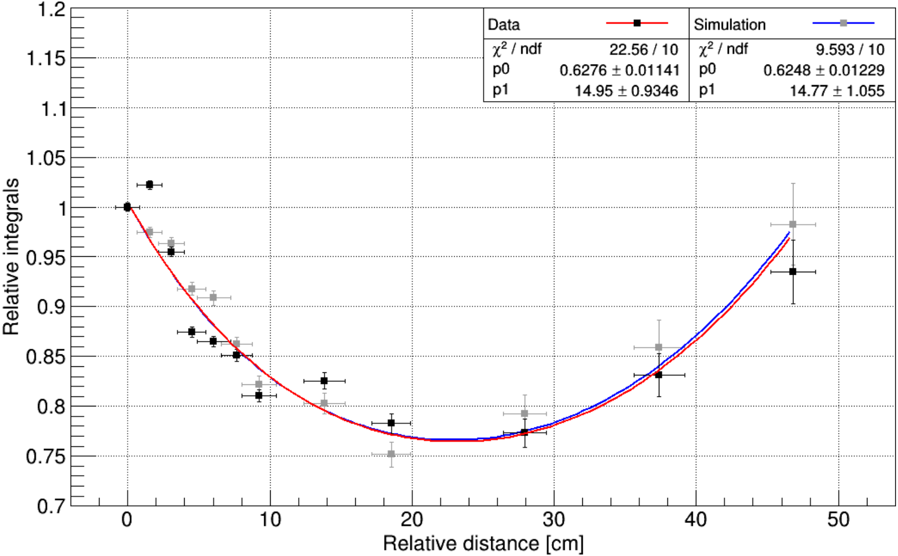
- Analyze each simulation with solid angle correction determined for another reflectivity
- Simulation parameters: α_{abs} = 15 cm, α_{scatt} = 70 cm, ly = 1600 γ/MeV (reflectivity 0)
- Data should behave like one of the analyzed simulations

Comparison with data



- Analyze data with solid angle correction determined for various reflectivities
- All bins that lie within 1σ uncertainty of the data fit are highlighted (black marker)
- Best match for reflectivity of the steel is 0 - 1% at 128 nm

Fit comparison of data and simulation



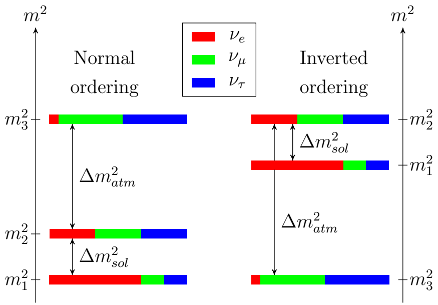
- Simulation α_{abs} = 15 cm, α_{scatt} = 70 cm, ly = 1600 γ/MeV, reflectivity 0 at 128 nm
- Fit of data results in $\alpha_{abs} = 14.95 \pm 0.93$ cm

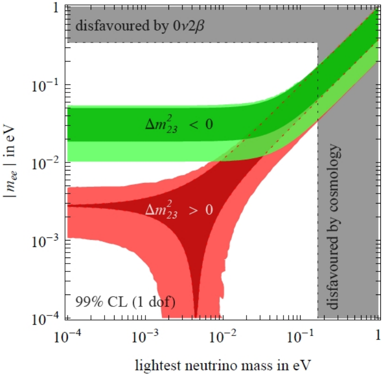
Conclusion

- Attenuation measurement has been performed in the GERDA cryostat
- Reflectivity of steel has been measured between 200 nm and 800 nm
- Determined solid angle correction and Cherenkov background with simulations
- Fit of data results in α_{abs} = 14.95 $\pm$ 0.93 cm with assumption of α_{scatt} = 70 cm and reflectivity 0 at 128 nm
- Simulation with α_{abs} = 15 cm, α_{scatt} = 70 cm, ly = 1600 γ/MeV, reflectivity 0 at 128 nm matches data very well
- Best match with data with reflectivity of steel between 0 and 1% at 128 nm

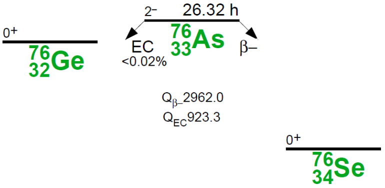
Backup

Neutrino physics

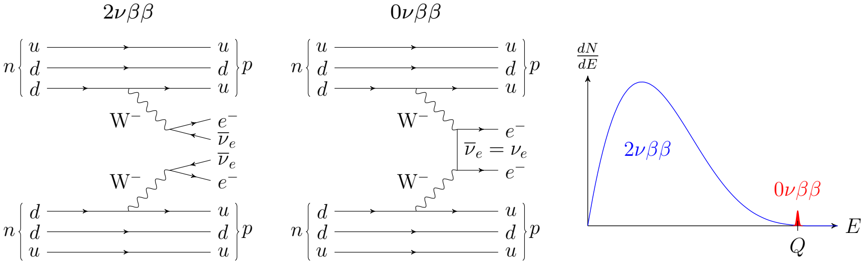




- Neutrino mass is zero in SM
- Neutrino oscillations $\rightarrow m_\nu \neq 0$
  $\rightarrow$ only sensitive to mass differences
- Which mass ordering is realized?
- Is the neutrino its own antiparticle?
  $\rightarrow$ investigation with 0νββ experiments
  $\rightarrow \left(T^{0\nu}_{1/2}\right)^{-1} \sim G^{0\nu} \cdot \left|\mathcal{M}^{0\nu}\right|^2 \cdot |m_{ee}|^2$

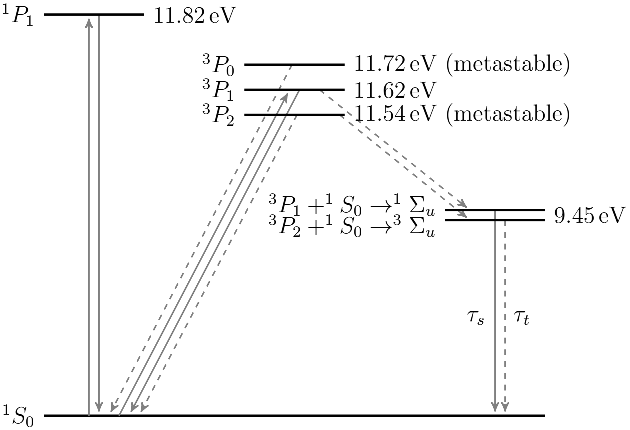


Double beta decay



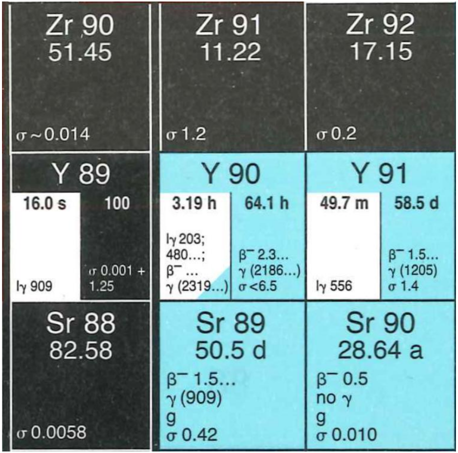
- 2νββ allowed in SM, only observable when β decay strongly suppressed
- If $\nu = \overline{\nu} \rightarrow 0\nu\beta\beta$ possible, violates lepton number ($\Delta L = 2$)
  $\rightarrow$ can be explained by light Majorana neutrinos (or other lepton number violating processes)
  $\rightarrow$ constraints on effective Majorana neutrino mass

Argon scintillation mechanism

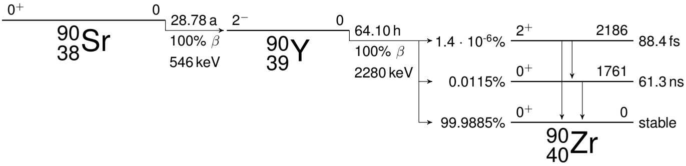


- Electron configuration of argon: [Ne](3s)^2(3p)^6 $\longrightarrow$ [Ne](3s)^2(3p)^5(4s)
- Radiation from $^1P_1$ and $^3P_1$ to $^1S_0$ ground state reabsorbed in argon
- Atom in $^3P_1$ and $^3P_2$ state can form molecule with $^1S_0$ argon atom
- γ's from Ar_2^* have not enough energy to be absorbed by $^1S_0$ argon atoms
- Peaks from singlet and triplet excimer decay are not resolved

^{90}Sr in the nuclide chart



Decay chain of ^{90}Sr



[Values from http://ie.lbl.gov/toi/]

Background estimation from setup

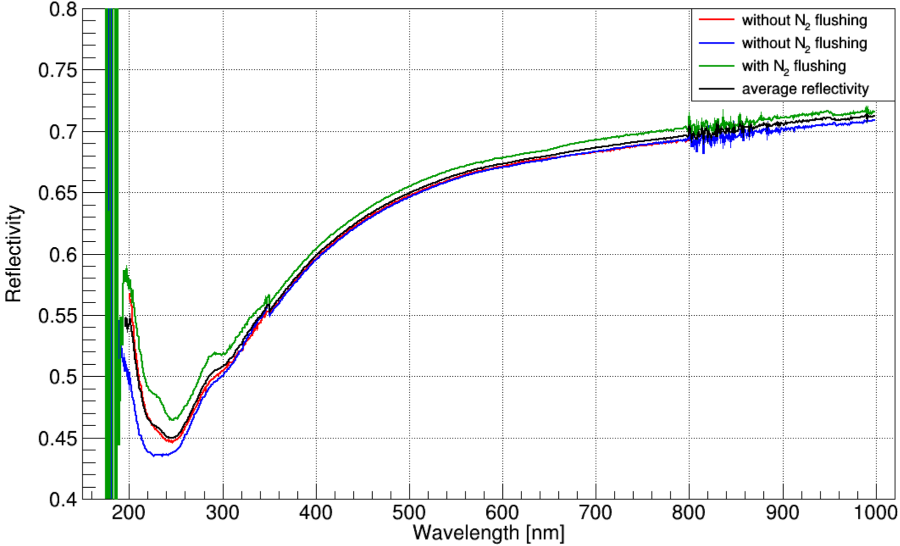
material	activity	amount	activity in setup
steel	550 mBq/kg	13 kg	7 Bq
argon	1.5 Bq/l	7 l	10.5 Bq

Activity from stainless steel:

isotope	activity [mBq/kg]
^{234}Th	< 200
^{214}Pb	< 25
^{214}Bi	< 25
^{228}Ac	70 ± 10
^{212}Pb	70 ± 10
^{208}Tl	70 ± 10
^{137}Cs	< 6
^{40}K	< 60
^{60}Co	17 ± 5

From http://radiopurity.in2p3.fr/

Comparison of various measurements of the steel reflectivity:



Reflectivity measurements IPF Dresden

Comparison of various measuring points for the diffuse reflectivity: