Background decomposition of the GERDA data with the Bayesian Analysis Toolkit

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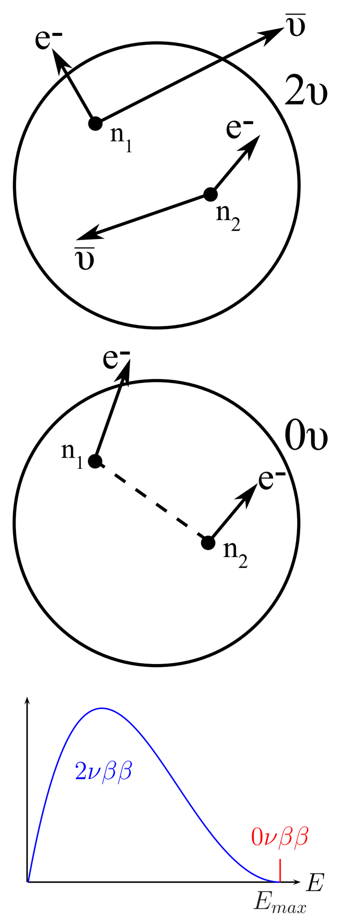
Abstract

GERDA is an ultra-low-background experiment designed to search for the neutrinoless double beta decay of Ge-76. The Bayesian Analysis Toolkit (BAT) was used to perform a full background decomposition of the GERDA Phase-I data. The Bayesian approach provides an all-in-one solution to handle prior knowledge, competing models and uncertainty propagation.

$0\nu\beta\beta$-Decay

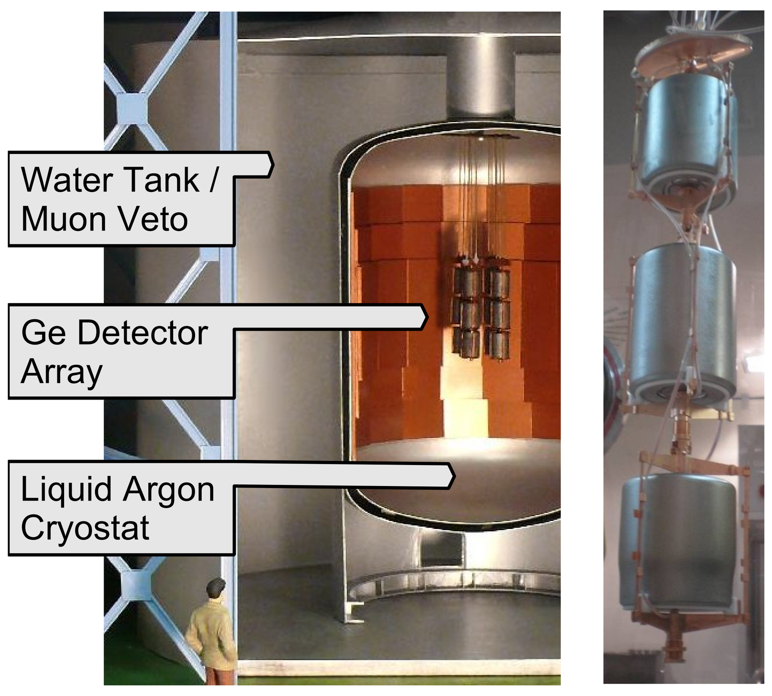


- Single β-decay energetically forbidden for some isotopes, only double β-decay ($2\nu\beta\beta$-decay and possibly $0\nu\beta\beta$-decay) allowed.
- If $0\nu\beta\beta$-decay (line spectrum) exists, ν must be a Majorana Particle ($\nu = \bar{\nu}$).

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G(Q, Z)\; |M_{\mathrm{nucl}}|^2\; \langle m_{ee}\rangle^2$$

- Study of $0\nu\beta\beta$-decay can
  - Discover lepton-number violation (several BSM processes).
  - Determine nature of ν (Majorana or Dirac).
  - Give information about absolute Neutrino mass and mass hierarchy?

The GERDA Experiment



- We are searching for $0\nu\beta\beta$ decay in ^{76}Ge at $Q_{\beta\beta} = 2039 keV$.
- Expected half-life $>= 10^{26}$ years!
- Array of isotopically enriched HPGe detectors, suspended in liquid Argon.
- Ultra-low background setup, located underground at Laboratori Nazionali del Gran Sasso (LNGS, Italy).
- Phase-I completed, Phase-II commissioning is underway.
- Three data sets for Phase-I: "Golden", "Silver" (lower data quality) and "BeGe" (different detector technology).
- Understanding of Phase-I background was (and still is) important for design and implementation of Phase-II!
- Challenge:
  - Multiple possible background sources (^{238}U- and ^{232}Th-series, ^{40}K, $^{42}Ar \rightarrow {}^{42}K$, ^{60}Co and ^{68}Ge and $2\nu\beta\beta$ decay of ^{76}Ge) in multiple possible locations.
  - Ultra-low background means low statistics.

The Bayesian Analysis Toolkit (BAT)

- Comprehensive C++ framework for Bayesian data analysis
- Features:
  - Parameter optimization (best fit) via Minuit or Simulated Annealing.
  - Marginalization and uncertainty estimation via Markov Chain Monte Carlo (MCMC) and other algorithms.
  - Direct comparison of model probabilities (Bayes factors).
  - Goodness-of-fit tests via generated data ensembles.
  - Freely programmable likelihood functions and data integration.
  - Support for ROOT functions and histograms.
- See also: F. Beaujean, The Bayesian Analysis Toolkit, Track 2, Thursday, 10:15

Method

- Construction of background models based on prior knowledge (material screening) and signatures in data (background ***gamma***-lines, time-variant vs. static parts of spectrum).
- Monte Carlo simulation of detector response to all possible background components in their credible locations.
- Fit of each complete model, including all prior knowledge and uncertainties, with BAT.

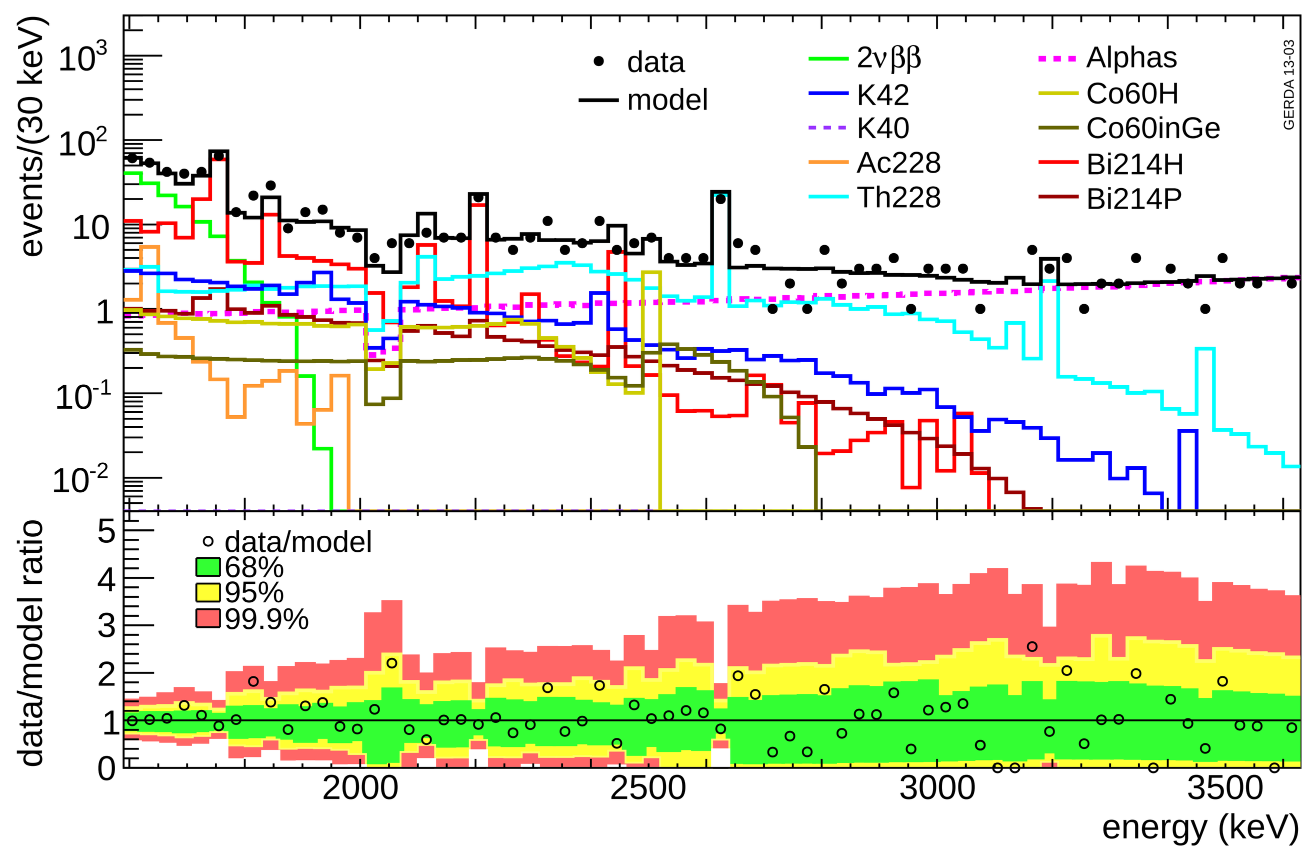
Advantages of the Bayesian Approach

$$P(\vec{\lambda}|\vec{D}, M) = \frac{P(\vec{D}|\vec{\lambda}, M)\cdot p_0(\vec{\lambda}|M)}{\int P(\vec{D}|\vec{\lambda}, M)\cdot p_0(\vec{\lambda}|M)\; d\vec{\lambda}}$$

- Answers the relevant question: "What and where are my background sources?" - frequentist approach would answer a different question.
- Simultaneous handling of (almost) any number of analysis-relevant and nuisance parameters - no profiling.
- Natural handling and automatic propagation of systematic uncertainties, as they become part of the model (prior knowledge).

Bayesian Background Fits

Exemplary fit result: Maximal background model, "Gold" dataset, central energy range:



Novel fit quality visualization: 1-σ, 2-σ and 3-σ credibility bands for data/model (best fit) in comparison with data.

Results

Best fit parameters with credibility intervals for different models*:

Source	Location	B [10^{-3} cts/(keV·kg·yr)]		
Dataset:		*Gold Coax (15.4 kg·yr)*		*BEGe (1.8 kg·yr)*
		Min. model	Max. model	Ext. min. model
alphas		2.4 (2.4, 2.5)	2.4 (2.3, 2.5)	1.5 (1.2, 1.8)
^{214}Bi	p$^+$ sur.	1.4 (1.0, 1.8)	1.3 (0.9, 1.8)	0.7 (0.1, 1.3)
^{214}Bi	n$^+$ sur.			
^{214}Bi	holders	5.2 (4.7, 5.9)	2.2 (0.5, 3.1)	5.1 (3.1,6.9)
^{214}Bi	LAr BH		3.1 (< **4.7**)	
^{214}Bi	Rn shr.		0.7 (< **3.5**)	
^{228}Th	holders	4.5 (3.9, 5.4)	1.6 (0.4, 2.5)	4.2 (1.8, 8.4)
^{228}Th	Rn shr.		1.7 (< **2.9**)	
^{228}Th	Heat ex.		0.015 (< **3.8**)	
^{60}Co	holders	1.4 (0.9, 2.1)	0.9 (0.3, 1.4)	(< **4.7**)
^{60}Co	Ge	0.6 (> **0.1**)	0.6 (> **0.1**)	1.0 (0.3, 1.0)
^{68}Ge	Ge			1.5 (> **6.7**)
^{42}K	LAr	3.0 (2.9, 3.1)	2.6 (2.0, 2.8)	2.0 (1.8, 2.3)
^{42}K	p$^+$ surf.		4.6 (1.2, 7.4)	
^{42}K	n$^+$ surf.		0.2 (0.1, 0.4)	20.8 (6.8, 23.7)
Global model		18.5 (17.6, 19.3)	21.9 (20.9, 23.9)	38.1 (32.2, 43.3)

∗Models differ by included background contributions
† Gaussian prior due to α-model; ‡ Strict parameter range due to the activation history
[N. Becerici Schmidt, Results on Neutrinoless Double Beta Decay Search in GERDA]

Clear constraints on nature and location of background sources!

References

- A. Caldwell, D. Kollar, K. Kröninger, BAT - The Bayesian Analysis Toolkit, Comput. Phys. Commun. 180 (2009) 2197-2219 (Homepage: https://www.mppmu.mpg.de/bat/)
- The background in the neutrinoless double beta decay experiment GERDA, EPJC 74 (2014) 2764
- N. Becerici Schmidt, Results on Neutrinoless Double Beta Decay Search in GERDA, Phd Thesis, MPP Munich