Double beta decay of ^{76}Ge into excited states of ^{76}Se in GERDA

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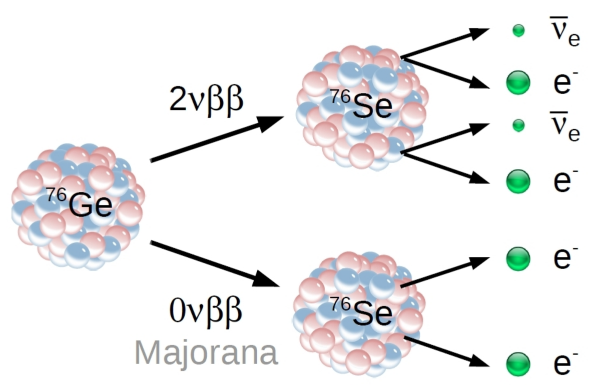
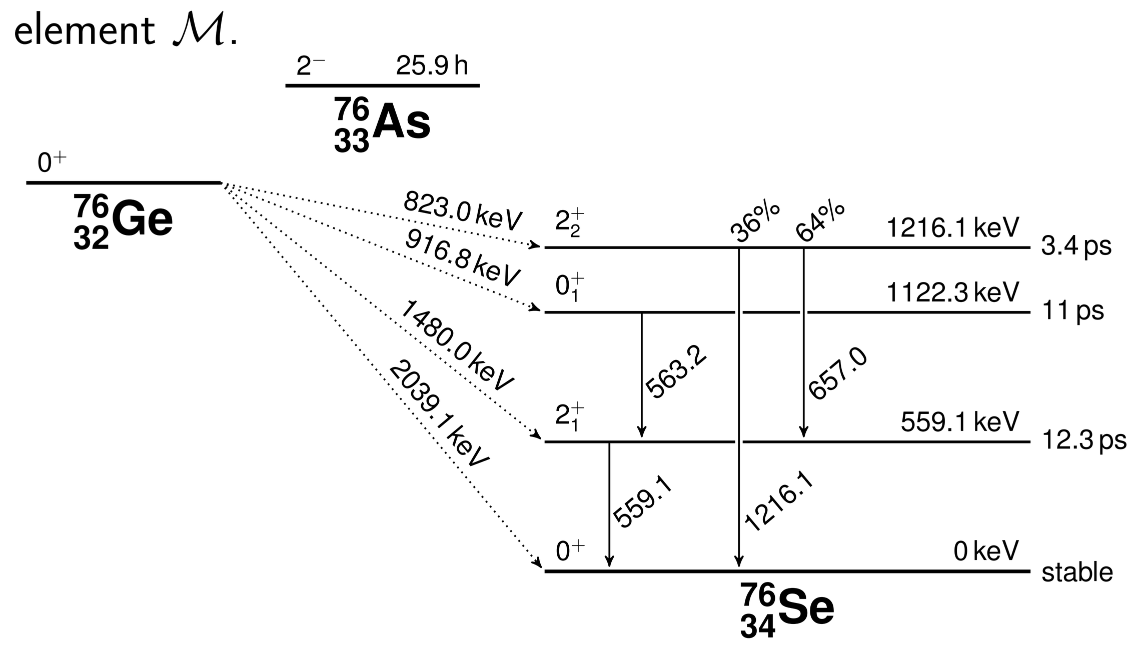
GERDA

Double beta decay

► The neutrino accompanied double beta decay (2νββ) is an allowed process in the Standard Model, but it is only observable if the single β decay is forbidden, e.g. for ^{76}Ge. If the neutrino is its own antiparticle, a so called Majorana particle, a double beta decay without neutrino emission, 0νββ, is possible. This process violates the lepton number conservation by two. If light Majorana neutrino exchange is the dominant process, the investigation of the 0νββ decay can constrain the effective Majorana neutrino mass m_{ee}, because it is connected with the half life $T_{1/2}$ of the decay via a phase space factor G and a nuclear matrix element $\mathcal{M}$.



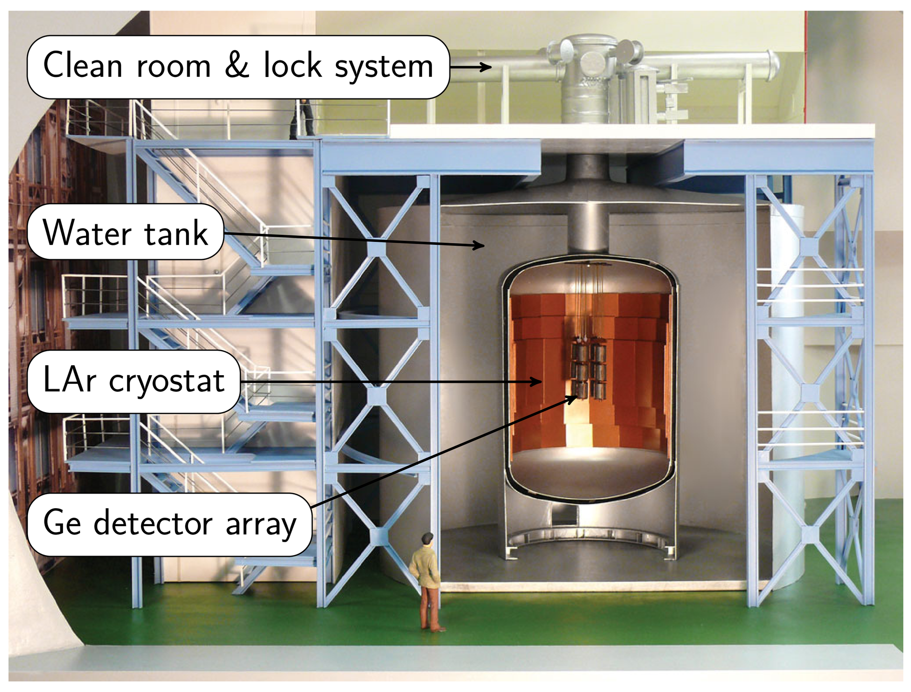
$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu} \cdot |\mathcal{M}^{2\nu}|^2$$
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2$$



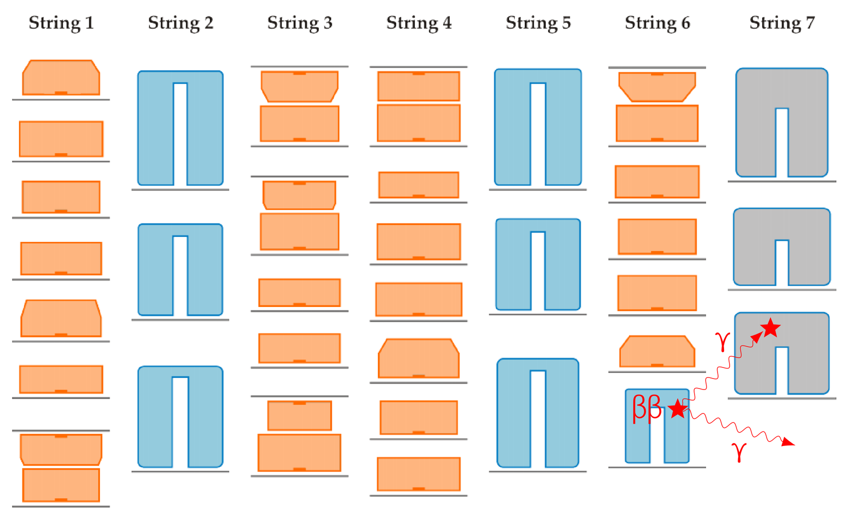
◄ ^{76}Ge cannot only decay into the ground state of ^{76}Se, but also into excited states (e.s.). The investigation of 2νββ into e.s. helps to constrain the nuclear matrix elements $\mathcal{M}^{2\nu}$ and $\mathcal{M}^{0\nu}$, which are numerically different but rely on similar assumptions.

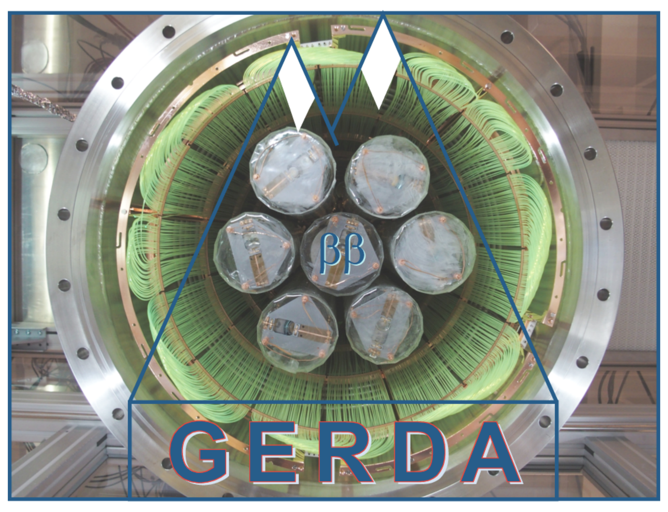
The GERDA experiment

► GERDA stands for Germanium Detector Array and is an experiment searching for 0νββ in ^{76}Ge. It uses germanium detectors which are enriched in ^{76}Ge and are operated bare in liquid argon (LAr), which serves both as a coolant and a shield for external radiation. For Phase II of GERDA it is planned to reach an exposure of 100 kg · yr with a background index of 10^{-3} cts/(keV · kg · yr).

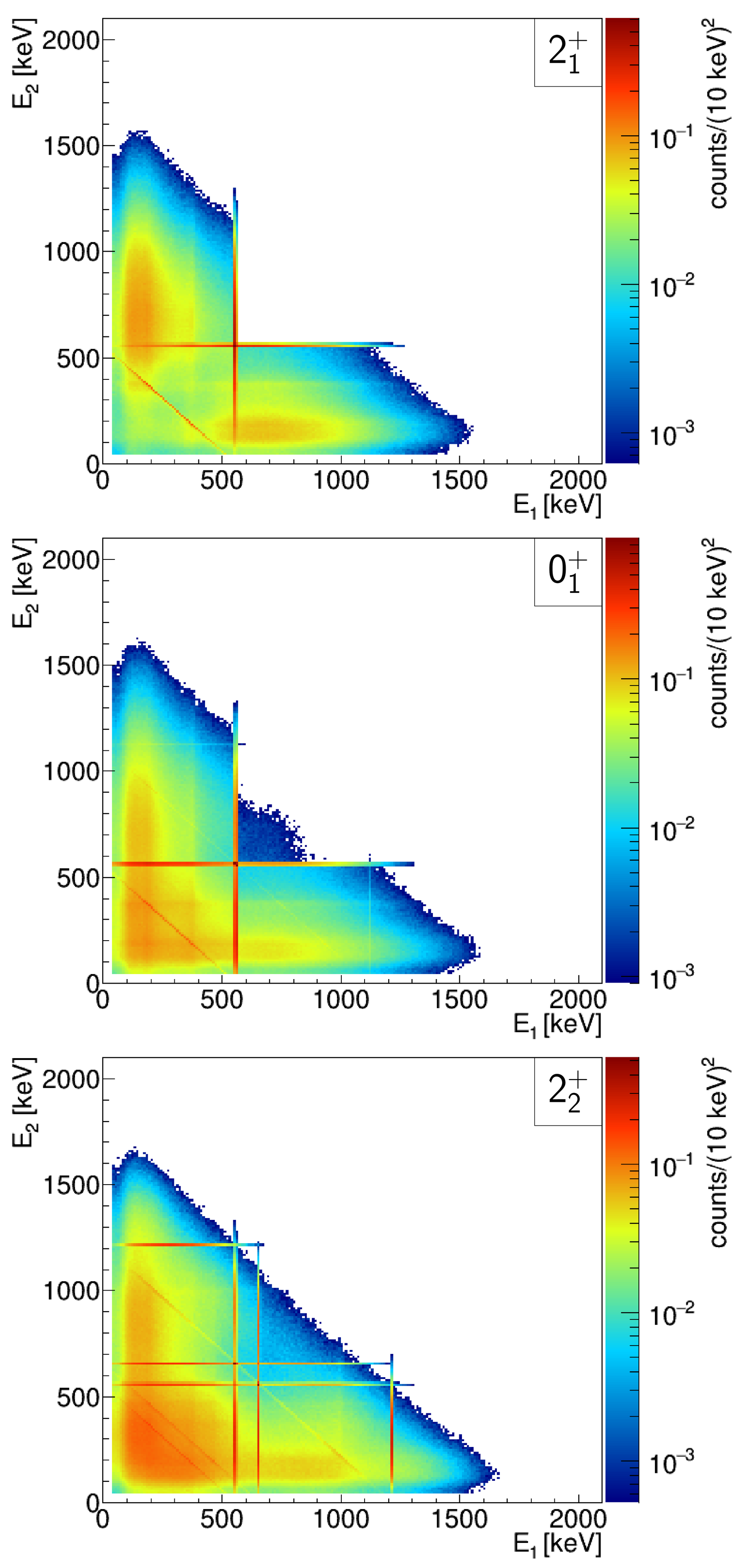


▼ GERDA Phase II operates 40 detectors in 7 strings in a close geometry. The granularity of the detector array is optimally suited to study ββ decays into excited states. While the two electrons of the ββ decay remain in the source detector, the de-excitation gammas can escape it and deposit energy in another detector. Thus the search for ββ decays into excited states is done investigating multiplicity 2 events.





MC signal signature from excited states

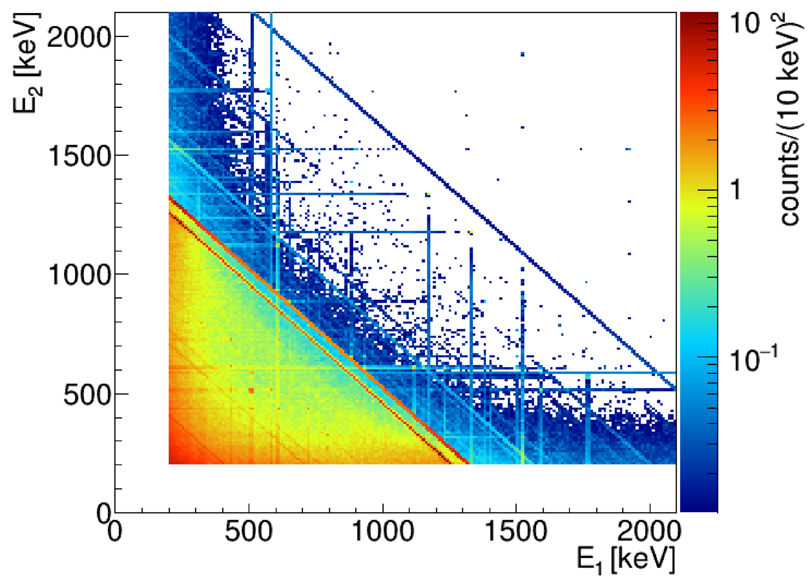


◄ The expected signal signatures are produced with MC simulations with 10^6 decays per detector. The decay particles are generated such that the angular correlation between the gamma rays is taken into account. Only so called multiplicity 2 events are shown in the 2D plots, where the energy depostion in two detectors are plotted versus each other.

The full energy depostion of the de-excitation gamma rays can be seen as horizontal and vertical lines. The diagonal lines are caused by gamma rays that share their full energy between two detectors. The ββ energy is not detected in some of these cases due to decays in the inactive volume of a detector or in detectors excluded from the analysis.

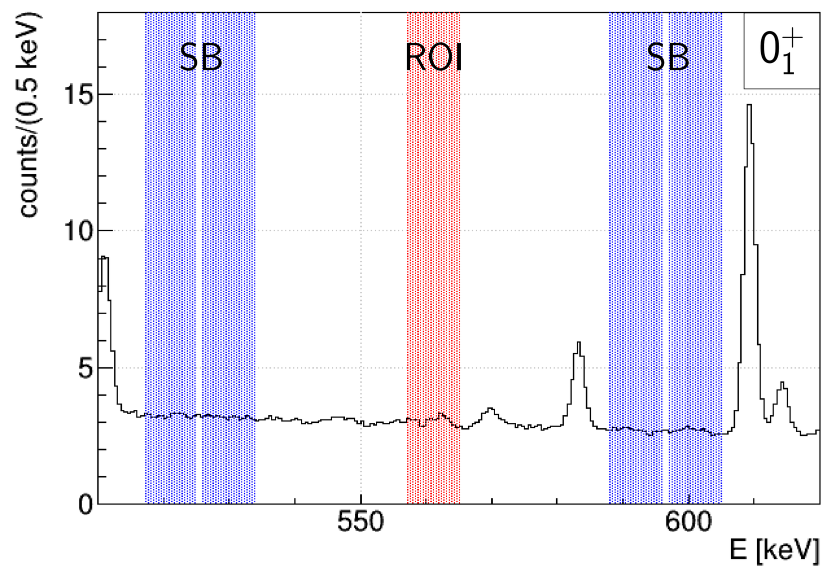
The region of interest (ROI) includes the horizontal and vertical lines, where one energy deposition is equivalent to a de-excitation gamma energy. Along these lines lies the continuous beta spectrum of the ββ decay superimposed with the gamma spectrum of partial energy depositions. In the 0_1^+ mode 17% of the simulated decays produce multiplicity 2 events, while 2.2% lie in the ROI. This corresponds to an efficiency increase of a factor of 2.5 to 3 for all investigated decay modes compared to Phase I of GERDA due to a more efficiently arranged detector setup.

Background estimation with MC simulation



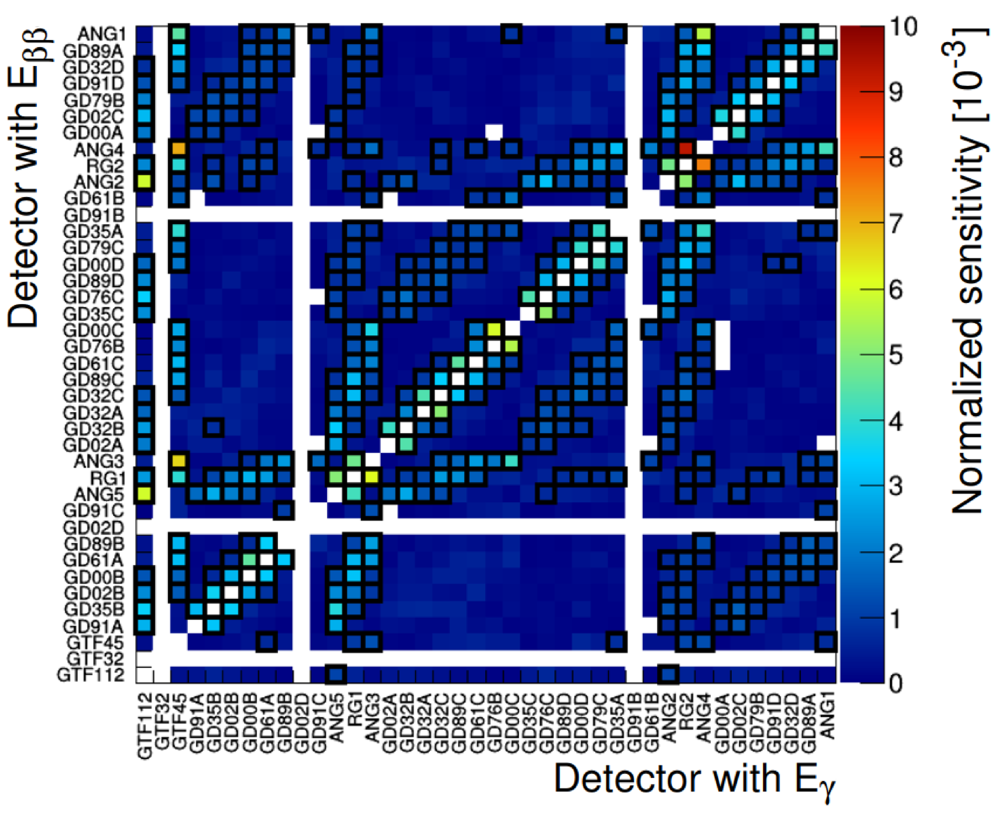
▲ The background for the search for decays into e.s. is estimated with the background model of GERDA Phase II, but only multiplicity 2 events are taken into account. Background components taken into account are selected according to screening results of each part of the detector array and the surrounding materials. The dominant background for this analysis originates from ^{42}K (50%) and ^{40}K (20%).

▼ Sidebands (SBs) are positioned symmetrically around the ROI. The positioning of the sidebands is verified and optimized with the background model to ensure that no gamma lines occur in them and that the background is flat or linear so that the average of expected SB counts is equal to the expected background counts in the ROI. The sensitivity of each decay mode is calculated from the MC background expectation. The analysis is based on counting the events in the ROI and SBs in the data, which makes it independent of the background model.



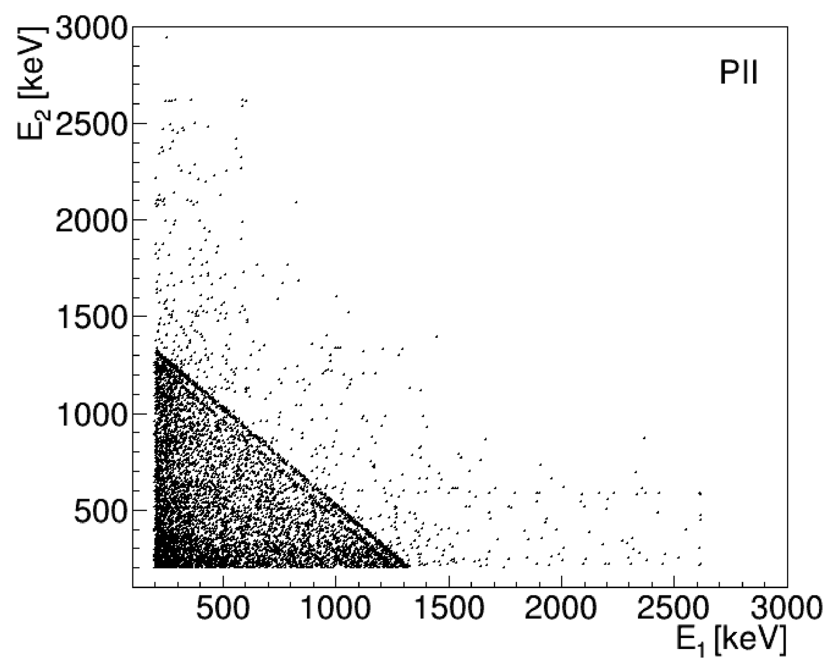
Detector pair selection – sensitivity optimization

► Neighboring detectors and strings as well as larger detectors have a higher probability to observe a full energy deposition of a de-excitation gamma. The sensitivity is optimized by selecting detector pairs for the analysis, which exhibit a high signal efficiency relative to the background. With their much higher energy than the de-excitation gammas, ^{42}K and ^{40}K contribute stronger to large distance pairs compared to the signal.



Preliminary results of GERDA Phase II data

▼ Spectrum of multiplicity 2 events accumulated for 35 kg · yr exposure in GERDA Phase II before all cuts. The diagonal lines from ^{42}K and ^{40}K are rejected, which leaves only ^{42}K and ^{40}K events with partial energy deposition as the main background.



$T_{1/2}^{2\nu}(0^+_{\text{g.s.}} \to 0^+_1)$ [yr]	Reference
$> 6.2 \cdot 10^{21}$ (90% CL)	Vasilev et al. (2002)
$> 2.7 \cdot 10^{23}$ (90% CL)	GERDA Phase I (2015)
$4.0 \cdot 10^{22}$	Civitarese, Suhonen (1994)
$4.5 \cdot 10^{22}$	Stoica, Mihut (1996)
$7.5 \cdot 10^{21}$	Aunola, Suhonen (1996)
$(1.0–3.1) \cdot 10^{23}$	Toivanen, Suhonen (1997)
$(1.2–5.8) \cdot 10^{23}$	Suhonen (2014)
$6.4 \cdot 10^{24}$	Iachello (2014)
$(2.3–6.7) \cdot 10^{24}$	Menendez (2014)

▲ Comparison of experimental limits and theoretical half life predictions for the 0_1^+ decay mode. With the current senstivity of $> 3.7 \cdot 10^{23}$ yr some of the older predictions can be ruled out. It is expected that with the sensitivity increase by the end of Phase II of GERDA the more recent half life predictions can be probed.

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