The GERDA Experiment: Search for the Neutrinoless Double Beta Decay

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The Germanium Detector Array (Gerda) experiment is searching for the neutrinoless double beta decay of ^{76}Ge. The observation of this Beyond the Standard Model process would prove the existence of a neutrino Majorana mass component and provide information on the neutrino mass hierarchy and absolute mass scale. Gerda operates enriched germanium diodes, acting simultaneously as the source and detector material, directly submerged in liquid argon. Phase I achieved the world's best lower limit of $T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{25}$ yr (90% C.L.). With the recent completion of the upgrade to Phase II, an additional 20 kg of germanium detectors – for a total of 35 kg – and a liquid argon veto system have been implemented. The goal is an order of magnitude lower background with a projected sensitivity of $1.4 \cdot 10^{26}$ yr for $T_{1/2}^{0\nu\beta\beta}$.

1 Matter antimatter asymmetry

Today, our universe is completely matter dominated. All galaxies and stars consist of baryons. Antimatter exists only as a product of high-energy particle collisions. In the early universe, this was not the case. According to the Standard Model of Particle Physics, the Big Bang should have created a completely symmetrical universe with equal amount of matter and antimatter. If this thought is developed further, the quark and antiquark pairs would interact in pairs leading to the complete annihilation of this symmetrical universe. In reality, a slight asymmetry introduced in the early stages of the universe is responsible for the small excess of matter in comparison to antimatter that now makes up our universe. The origin of this asymmetry could lie in neutrino nature. Determining the nature of the neutrinos is thus of fundamental importance in modern physics [1].

2 Neutrinos

In 1937, Ettore Majorana suggested that the neutrino could be its own antiparticle [2]. The recent discovery of neutrino oscillations establish the non-zero mass of neutrinos [3, 4]. The matter antimatter asymmetry could be explained through an extension of the Standard Model, wherein the see-saw mechanism introduces right-handed neutrinos. CP violating decays of these particles then spontaneously generate leptons resulting in a lepton asymmetry in the early universe. Baryogenesis via leptogenesis could thus lead to the observed matter antimatter asymmetry [5]. The prime avenue to directly probe this fundamental characteristic and simultaneously obtain information on the absolute neutrino masses is the neutrinoless double beta decay. This postulated decay channel could involve two Majorana neutrinos, which annihilate off-shell in a lepton number violating interaction with zero neutrinos in the final state.

3 The GERDA experiment

The Germanium Detector Array (GERDA) experiment is searching for the neutrinoless double beta decay of ^{76}Ge. It is located underground in Hall A of the Laboratori Nazionali del Gran Sasso (LNGS) with a 1400 m rock overburden. The isotopically enriched germanium diodes are directly submerged inside a 64 m^3 high purity liquid argon cryostat and act simultaneously as the source and detector material. Surrounding the cryostat, a 10 m diameter purified water tank shields the experiment and serves as a Cherenkov muon veto featuring 66 photomultiplier tubes (PMTs). These shielding and veto layers ensure a substantial reduction of the background and the highest possible sensitivity for the experiment [6].

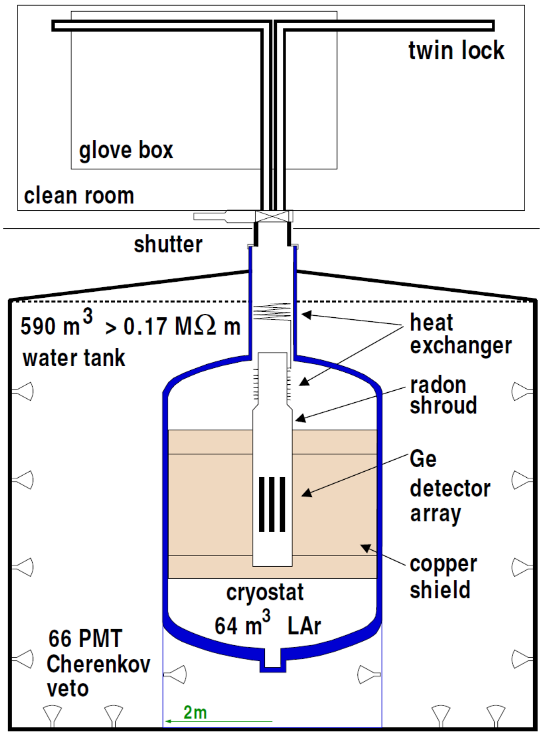

Figure 1: The GERDA experiment with its germanium detector array directly submerged in a liquid argon cryostat, surrounded by a water tank Cherenkov muon veto.

The germanium detectors offer an excellent energy resolution of ∼ 0.15% FWHM at $Q_{\beta\beta}$. Another advantage is the possibility of Pulse Shape Discrimination (PSD), wherein the induced signal shapes are used to further reduce the background by identifying single site events (e.g.

$0\nu\beta\beta$), multi site events (e.g. Compton scattered γ), and surface events (e.g. α/β events).

Background reduction techniques are crucial as the sensitivity on the half-life of the neutrinoless double beta decay strongly depends on the background index (BI) as follows

$$\mathrm{T}^{0\nu}_{1/2} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}. \tag{1}$$

Only in a zero background regime can a proportional scaling to the exposure ($M \cdot t$) be attained such that

$$\mathrm{T}^{0\nu}_{1/2} \propto M \cdot t. \tag{2}$$

4 GERDA Phase I

In GERDA Phase I, running from November 2011 to May 2013, 15 kg of semi-coaxial and 3 kg of Broad Energy (BEGe) germanium detectors were used on four strings for a total exposure of 21.6 kg · yr. A tenfold lower background in comparison to previous experiments was obtained with a background index of around $1 \cdot 10^{-2}$ counts/(keV · kg · yr) at $Q_{\beta\beta}$, fulfilling the design goal. Figure 2 shows the best fit background model including the individual contributions, performed before unblinding a 40 keV window around $Q_{\beta\beta}$ [7].

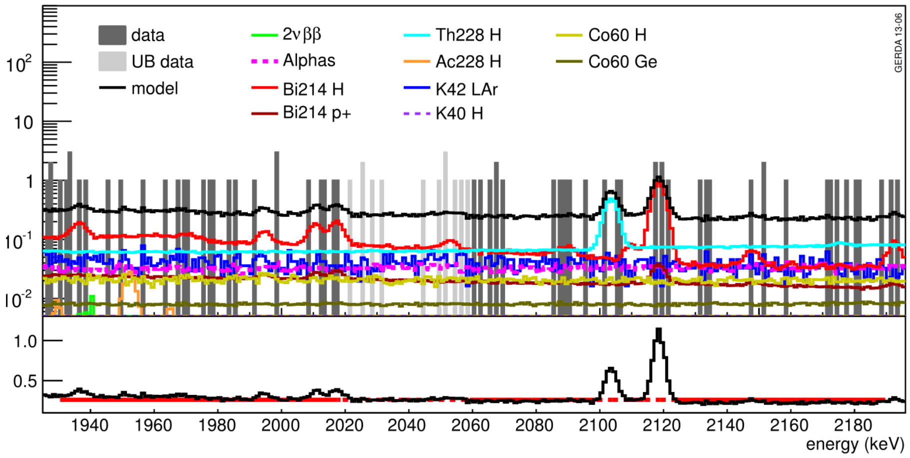

Figure 2: Phase I background best fit minimum model and individual contributions. The data inside the blinded window (UB, light grey) of size 40 keV is excluded from the fit. Figure from [7].

With this progress, it was possible to achieve the world's best lower limit of $T^{0\nu\beta\beta}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for the half-life of the neutrinoless double beta decay of ^{76}Ge. Figure 3 depicts the region of interest, the relevance of the PSD, and the lower limit [8].

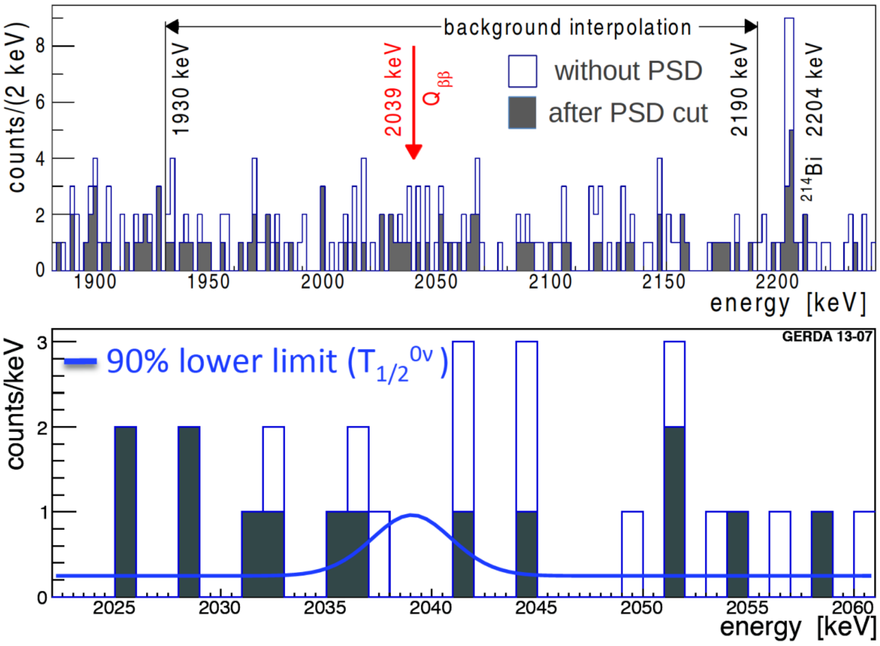

Figure 3: The results of Gerda Phase I in the region of interest (with and without PSD), leading to the lower limit of $T_{1/2}^{0\nu\beta\beta}$. Figure from [8].

5 GERDA Phase II

For Phase II of the experiment, the active mass of germanium diodes is increased by an additional 20 kg of BEGe detectors for a total of 40 detectors on 7 strings. The BEGe detectors offer superior PSD capabilities. A liquid argon hybrid veto system was introduced through the installation of PMTs and an optical fibre curtain coupled to silicon photomultipliers (SiPMs) inside the cryostat. The detection of liquid argon scintillation light is used to reject external background events. Combining all developments, the background can thus be efficiently reduced by an order of magnitude. The goal is to achieve a median sensitivity of $T_{1/2}^{0\nu\beta\beta} \sim 1.5 \cdot 10^{26}$ yr for a total exposure of 100 kg · yr. Table 1 summarises the Phase I and the aim of Phase II [9]. The upgrade to Gerda Phase II has been finished and the data taking has begun in December 2015.

Phase	Active Mass [kg]	BI [counts/(keV·kg·yr)]	$T_{1/2}^{0\nu}$ Sensitivity [yr]
I (finished)	15	10^{-2}	$2.1 \cdot 10^{25}$
II (expected)	35	10^{-3}	$1.4 \cdot 10^{26}$

Table 1: Gerda Phase I results and Phase II goals in terms of the active detector mass, background index and median sensitivity on the ^{76}Ge neutrinoless double beta decay half-life.

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