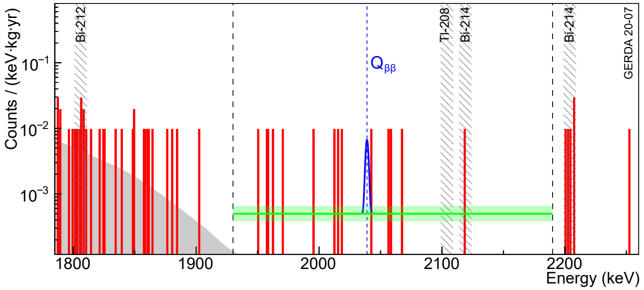

*Energy spectrum of the registered signals (counts, red). The green line indicates the level of background signals in the region of interest around $Q_{\beta\beta}$. The blue line corresponds to the intensity of a hypothetical signal with a half-life of $1,8 \times 10^{26}$ years. Grey area: energy distribution of the $2\nu\beta\beta$ decay; hatched bars: energy windows of lines of known radioactive decays.*

unprecedented precision the half-life of the two-neutrino double beta decay to be $2 \times 10^{21}$ years. However, it didn‘t find the neutrinoless double beta decay, but improved the lower limit of its half-life to $1,8 \times 10^{26}$ years – this is by 16 orders of magnitude longer than the age of the Universe! With LEGEND-1000 it should finally be possible to measure half-lives in the order of $10^{28}$ years.

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## Contributions of MPIK

The GERDA experiment was initiated by MPIK in 2004, and performed by a collaboration of 15 European institutes. Further institutes from Europe as well as from America and China joined the collaboration for LEGEND. Major MPIK contributions to GERDA included the design and supply of the huge cryostat filled with liquid argon, the refurbishment of enriched diodes from previous experiments, the low-mass detector holders and the data acquisition system including software. Last but not least, MPIK researchers led the process of screening and validating the highly pure construction materials. Here, the long-standing experience in low-level techniques, i. e., the ability to detect the very lowest levels of radioactivity, was crucial. In addition, the MPIK provided a detector test facility and developed parts of the liquid-argon veto deployed from the second measurement phase. The MPIK plays the central role in the upgrade of GERDA to LEGEND-200 being responsible for the production of additional detectors, the mechanical installation and the data acquisition system.

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The Max-Planck-Institut für Kernphysik (MPIK) is one of 86 institutes and research establishments of the Max-Planck-Gesellschaft. The MPIK does basic experimental and theoretical research in the fields of Astroparticle Physics and Quantum Dynamics.

# Are Neutrinos Majorana Particles?

## GERDA / LEGEND-200

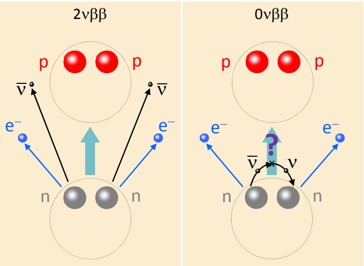
# Are Neutrinos Majorana Particles?

# GERDA/LEGEND-200

*Besides photons, neutrinos are the most abundant particles in the Universe. However, we don't recognize them, since they interact only weakly with matter. A possible, very remarkable property has been proposed by Ettore Majorana in the 1930s: In contrast to all other particles constituting the matter surrounding us, neutrinos may in fact be identical with their antiparticles. If true, this important property would lend credibility to a number of novel theoretical concepts that may considerably enlarge our understanding of the constitution of matter and of the development of the Universe.*

## The Double Beta Decay and the Neutrino

In single beta decay, a neutron within a nucleus decays to a proton, an electron (β particle), and an antineutrino. However, there are a few isotopes (one of which is ${}^{76}$Ge), in which single beta decay is not allowed due to energy conservation reasons, whereas the simultaneous conversion of two neutrons with the emission of two antineutrinos (2νββ) is possible. If neutrinos are identical with their antiparticles, i.e., are Majorana particles, double beta decay without emission of neutrinos should also occur, but at an extremely low rate. In that case, the antineutrino from one beta decay is absorbed by the second beta-decaying neutron, which is only possible if neutrinos and antineutrinos are indeed identical.

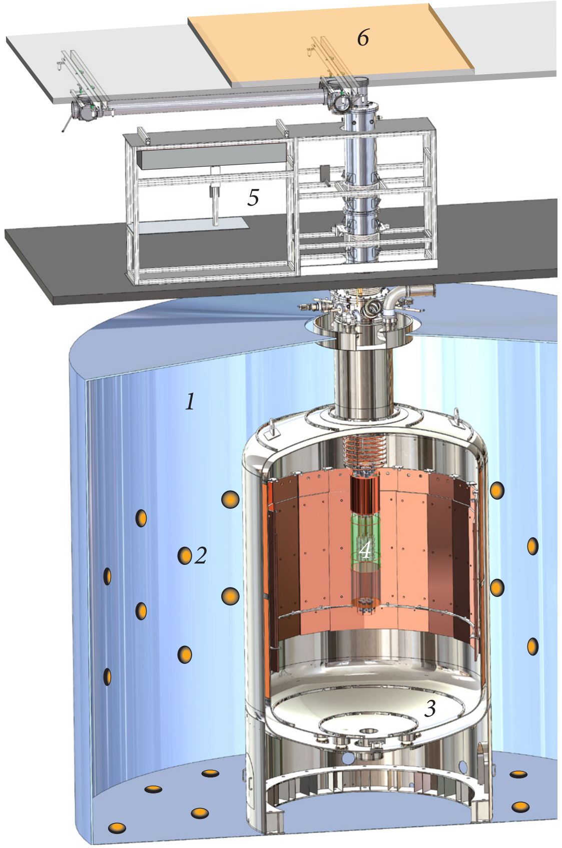


The search for the neutrinoless double beta decay (0νββ) is done by measuring the energy of the two emitted electrons. If the sum of their energies corresponds to the total energy of the decay ($Q_{\beta\beta} = 2039$ keV for ${}^{76}$Ge), then neutrinoless double beta decay has occurred. On the other hand, two-neutrino double beta decay (2νββ) is characterised by the fact that the total energy of the electrons is smaller, because part of the energy is delivered to the outgoing antineutrinos.

## GERDA and LEGEND

In GERDA (germanium detector array) and its successor experiment LEGEND-200 (large enriched germanium experiment for neutrinoless ββ decay) the germanium isotope ${}^{76}$Ge is used as the source and simultaneously the detector of double beta decay. Germanium is suitable for the production of semiconductor detectors (diodes) that exhibit a very good energy resolution. The experiments use germanium specifically enriched from naturally 8% to about 88% ${}^{76}$Ge.

GERDA started in autumn 2011 with germanium diodes with a total mass of 15 kg und reached in its final state about 40 kg ${}^{76}$Ge. The measurements proceeded until end of 2019. With the upgrade to LEGEND-200, the mass will be increased stepwise up to 200 kg. A later new installation with up to 1 tonne germanium is already being planned (LEGEND-1000).



*Setup of GERDA and LEGEND-200: water tank (1) with light sensors (2), therein liquid argon-cryostat (3) with Ge detectors(4), above it cleanroom (5) and plastic scintillator plates (6).*

The germanium diodes are hanging in a tank filled with liquid argon, which in turn is installed inside a huge tank filled with high-purity water, and all this is located in the Italian Gran Sasso underground laboratory. But why this huge effort?

## Suppression of Radioactive and Cosmic Radiation

Searching for a needle in a haystack is trivial compared to the detection of double beta decay, since environmental radioactivity is a background at least a billion times stronger than that decay. Indeed, the decay of a number of different radioactive isotopes as well as cosmic radiation may be so copious that a 0νββ decay can't be identified unambigiously. It is therefore extremely important to keep these radioactive substances and radiation away from the detector.

The detector crystals and the surrounding detector parts were therefore very carefully chosen and processed. In addition, observation of the extremely rare process requires very elaborate techniques to further suppress backgrounds from cosmic particles, natural radioactivity of the surroundings and even from the experimental structure itself.

The holders of the germanium detectors consist of only a few grams of high-purity copper. Also, argon can be produced to be extremely clean and it absorbs radioactive radiation from the surrounding components. The thereby produced light is detected and serves as „veto". The –186 °C cold liquid argon efficiently cools the germanium crystals improving their energy resolution. These are mounted in strings (see title picture) and surrounded by a shielding wrapping. In the outer water tank and by plastic scintillator plates installed above it, passing cosmic radiation is detected. Only by combining all of these innovative and pioneering techniques, it was possible to reduce the background to the world-wide lowest level.

## Results of GERDA

GERDA has reached all of its envisaged goals and collected in several measurement phases overall 127 kg·years of data. To assure an as unprejudiced as possible data analysis, the data in the signal region was blinded and the scientists focused on optimising the data analysis procedures until all calibrations and cuts were fixed. Already in its first measurement phase, GERDA succeeded to measure with