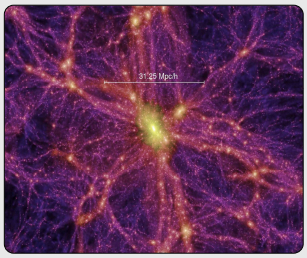
GERDA – Germanium Detector Array

searching for the

Neutrinoless Double Beta Decay



Neutrinos and Cosmology

In the hot early Universe, neutrinos were created and annihilated in equilibrium with other particles, in particular with photons:

$$\nu_\mu + \nu_\mu \leftrightarrow \gamma + \gamma$$

As the Universe expanded, it cooled down and around 1 s after the Big Bang the energy of neutrinos was so low that such processes could no longer occur and their number density was fixed to this day.

This number is very similar to the one of the photons in the observed Cosmic Microwave Background Radiation, the so-called 'afterglow' of the Big Bang, making neutrinos the second most abundant particles in the Universe.

Because these relic neutrinos have a predicted temperature of about 1.95 Kelvin, they are extremely difficult to detect in the laboratory. Nonetheless, it is possible to verify the existence of cosmic neutrinos indirectly via their effect on structure formation.

Neutrinos left over from the Big Bang could provide the dark matter in the Universe if the sum of their mass would be around 12 eV. This is above the direct experimental limits for electron neutrinos, but acceptable for the other two species.

However, because light neutrinos move rapidly and can escape gravitational potentials until fairly late in the Universe, preventing the formation of galaxies, they are not thought to be good dark matter candidates.

Nonetheless, knowing their mass precisely would give us a clear picture about their role in the formation of observed structures in our Universe.

Neutrinos may be responsible for the dominance of matter over antimatter in the observable Universe and hence for our very existence! Such scenarios, in which primordial, heavy neutrinos must have decayed more likely to particles than to anti-particles could be tested by the observation of the rare decay process called neutrinoless double beta decay.

The relevance of double beta decay

I. Is the neutrino its own antiparticle?

While the electron e^- and the positron e^+ are clearly different particles, having opposite values of electric charge, such a distinction is not obvious in the case of the neutrino, which is an electrically neutral particle.

$$\nu = \bar{\nu} \; ?$$

The question was first raised by Ettore Majorana in 1937. While Dirac's theory leads to 4 possible states of a neutrino - particle and antiparticle, each right-handed or left-handed - Majorana's theory leads only to two states: the right-handed (ν_{RH}) and left-handed (ν_{LH}) versions of a single particle:

momentum ⟵ spin $\quad \nu_{LH}, \nu_{RH} \quad$ momentum ⟶ spin

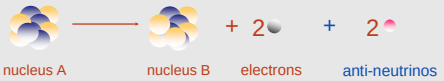
This central problem in neutrino physics is unsolved to this day, and the observation of a the neutrinoless double beta decay could provide the answer!

Paul Dirac (1902 - 1984)

Ettore Majorana (1906 - 1938?)

II. Double beta decay?

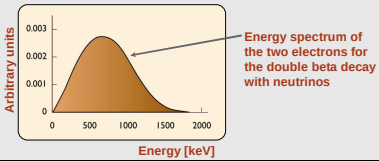
Back in 1935, Maria Goeppert-Meyer was investigating an unusual form of the beta-decay, in which two neutron change to two protons almost simultaneously. The resulting nuclei are lighter than the initial ones, and four particles are emitted in the decay, two electrons and two anti-neutrinos:



nucleus A — nucleus B — electrons — anti-neutrinos

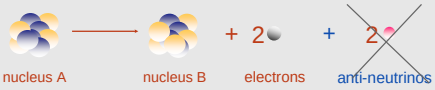
Since it involves the weak force twice, the process is very rare, albeit observable. With a half-life on the order of 10 billion times the age of the Universe (which is 14 billion years old), it has been seen in a number of even-even nuclei: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U.

Just like in the standard beta decay, the energy spectrum of the emitted electrons in continuous (since energy can be carried away by the neutrinos, which leave no trace in the detector):



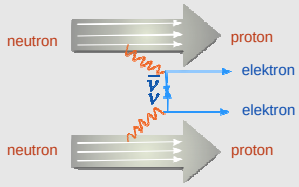
III. Neutrinoless double beta decay?

Four years later, Wendel Furry realized that a different form of double beta decay is possible if the neutrino is a Majorana particle. Thus, if the neutrino is its own antiparticle, the neutrino emitted by the one neutron can be reabsorbed by another neutron to yield two protons plus two electrons, but no neutrinos:



nucleus A — nucleus B — electrons — anti-neutrinos

The neutrino plays a virtual role, participating in the process only at the unobserved quantum level:



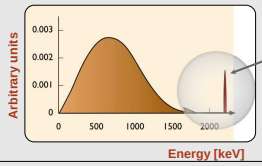
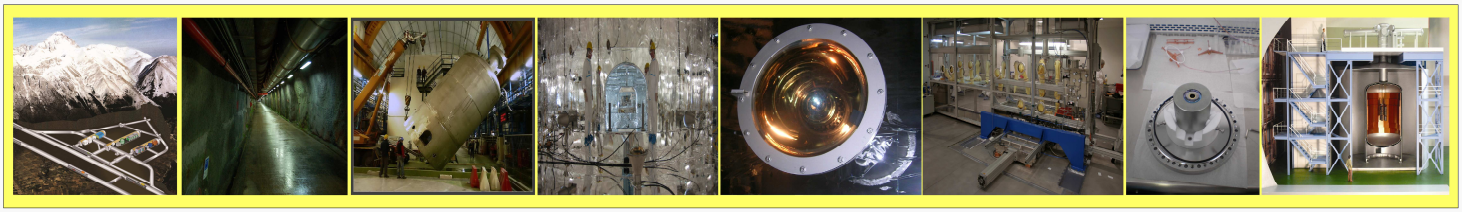
However, we know that the neutrino emitted by the first neutron is right-handed (ν_{RH}) and that it needs to be left-handed (ν_{LH}) in order to be reabsorbed by another neutron.

Can the neutrinoless double beta decay occur at all?

IV. What is the mass of neutrinos?

According to quantum theory, if the neutrino has mass it must exist as a mixture of both left-handed and right-handed states. Hence, the neutrino emitted by a neutron has some chance of being a left-handed particle and thus to be reabsorbed by another neutron - and the neutrinoless double beta decay can occur!
The probability depends on the mass of the neutrino - the heavier it is, the more likely the process will arise.

If an experiment discovers the decay, it will show both that neutrinos are Majorana particles and that they have mass, which will be revealed by the rate at which the process occurs.

But how can we tell whether or not two invisible neutrinos were emitted at the same time as the detected electrons?

By looking at the energy spectrum of the electrons - if there are no neutrinos, the electrons will emerge with a unique energy and the sum spectrum will be a spike, rather then a broad continuum: