

Introduction

Why does one look for the neutrinoless double beta decay?

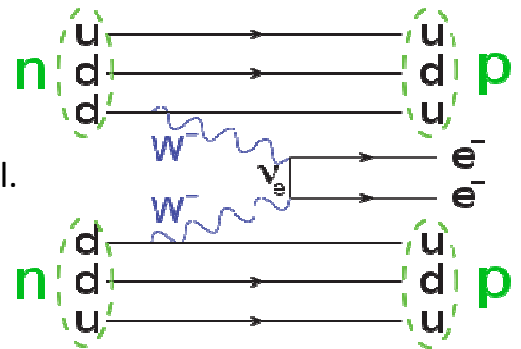
The nature of the neutrino can be determined. Is the neutrino a Dirac-Fermion or a Majorana-Fermion? When the neutrinoless double beta decay is observed the lepton number conservation is violated and this would mean physics beyond the Standard Model! Last but not least the neutrinoless double beta decay offers means to determine the neutrino mass.

What is the neutrinoless double beta decay?

The double beta decay is basically two beta decays happening simultaneously. This is why it is a second order process of the weak interaction and a 4th order process in the Glashow-Weinberg-Salam model.

One neutron decays into a proton, an electron and a neutrino. When this neutrino interacts with the neutron it creates a second electron and a second

proton. Of course this is possible only if the neutrino is its own antiparticle! So there are two different kinds of double beta decay: the two neutrino double beta decay and the neutrinoless double beta decay.



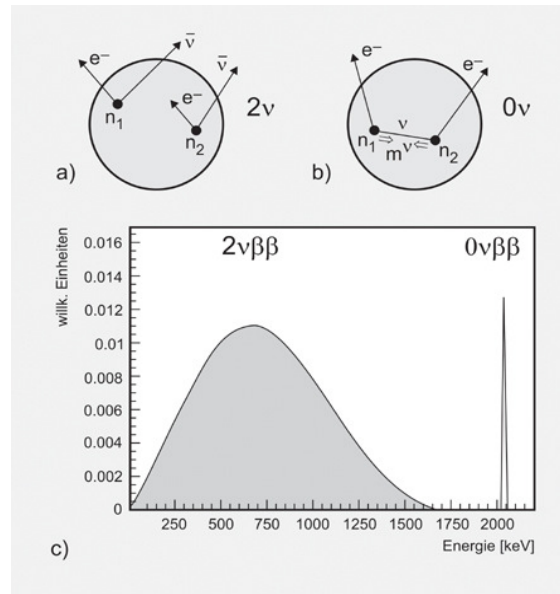
$$(Z, A) \rightarrow (Z + 2, A) + e_1 + e_2 + \bar{\nu}_1 + \bar{\nu}_2 \quad 2\nu\beta\beta$$

$$(Z, A) \rightarrow (Z + 2, A) + e_1 + e_2 \quad 0\nu\beta\beta$$

One can easily see that the neutrinoless double beta decay violates the lepton number conservation and thus means physics beyond the Standard Model.

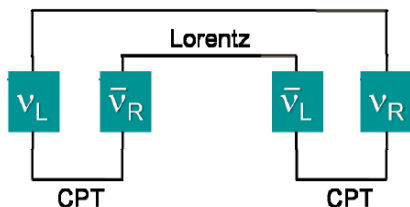
Double beta decay plot

Since the two neutrino double beta decay is a four particle decay process the electron energy spectrum is continuous whereas the neutrinoless double beta decay is a two particle decay and which results in a sharp peak in the energy sum spectrum at the Q-value of the decay.

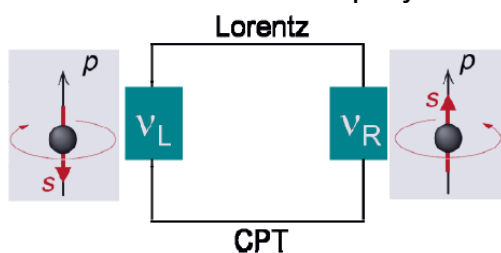


Dirac or Majorana neutrino?

One important question about the neutrino that could be answered by the neutrinoless double beta decay concerns its very nature. Is it a Dirac-Fermion or a Majorana-Fermion? Dirac-Fermions have four distinct states, where charge conjugation transforms the fermion into its antiparticle. Application of the P-operator changes the handedness. So far only left-handed neutrinos and right-handed antineutrinos have been observed.



In contrast the Majorana-Fermion is charge self-conjugated, which means it is its own antiparticle. So when applying the CPT-Transformation, it only changes its handedness. For a massive neutrino a Lorentz-Boost also changes the handedness, since one can always find a coordinate-system faster than the neutrino for which the projection of the spin onto the momentum would flip.



So far no Majorana-Fermions are known and the observation of the neutrinoless double beta decay would prove the Majorana nature of the neutrino, since according to the weak interaction the neutron would

only interact with a neutrino and not with the emitted antineutrino. By giving up the concept of neutrino & antineutrino this process is allowed.

Theory

Requirements for the neutrinoless double beta decay

Particle physics requirements

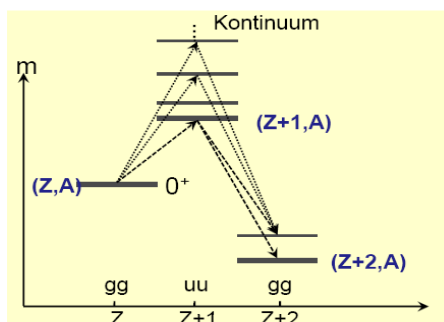
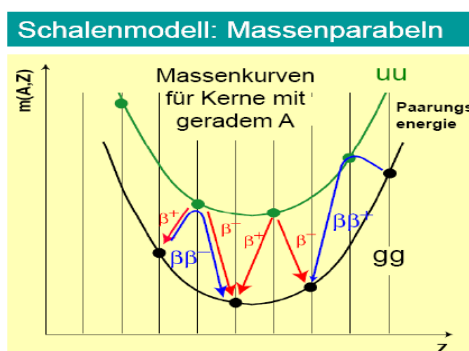
One requirement is the Majorana nature of the neutrino as discussed above. The other is that the neutrino must have mass. Only when the neutrino has mass a handedness change can occur and the emitted right-handed neutrino changes to a left-handed neutrino which can be absorbed by the neutron, since the known weak interaction is only left-handed. In gauge theories there is a theorem which says, that if the neutrino has mass there is also a small fraction of right-handed weak interaction.

Nuclear physics requirements

A nuclear decay is allowed if the energy of the daughter nucleus is lower than the mother nucleus. The Bethe-Weizäcker formula

$$m(Z, A = const.) \sim \alpha Z + \beta Z^2 + \delta_p$$

, where δ_p is the pair energy term which is negative for even/even nuclei and positive for odd/odd nuclei and 0 for all other, gives the graph below:



A single beta minus decay from even/even nucleus on the far left of the parabola is energetically not allowed but the double beta decay is. If the single beta decay is also allowed the rate of this decay is much higher than the double beta decay and thus the double beta decay is suppressed and not observable. The even/even nucleus decays through a continuum of virtual intermediate states which are odd/odd.

Table of isotopes that undergo double beta decay

Isotope	Q-Value [MeV]	Isotopic abundance	Observed half-life [y]
48-Ca	4.271	0.0035 %	$4.0 \cdot 10^{19}$
76-Ge	2.039	7.8%	$1.4 \cdot 10^{21}$
82-Se	2.995	9.2%	$0.9 \cdot 10^{20}$
96-Zr	3.350	2.8%	$2.1 \cdot 10^{19}$
100-Mo	3.034	9.6%	$8.0 \cdot 10^{18}$
116-Cd	2.802	7.5%	$3.3 \cdot 10^{19}$
128-Te	0.868	31.7%	$2.5 \cdot 10^{24}$
130-Te	2.533	34.5%	$0.9 \cdot 10^{21}$
136-Xe	2.479	8.9%	Not obs.
150-Nd	3.367	5.6%	$7.0 \cdot 10^{18}$

A high Q-value is preferred because then the signal is easier to discriminate from the natural radioactivity. A high natural isotopic abundance is also preferred since enriching costs a lot of money. The observed half-lives are measured for the two neutrino double beta decay, which is much more common than the neutrinoless double beta decay. One can already see that measuring the half life of such a rare process poses a lot of problems for the experimentalists.

Determine the neutrino mass from measured half-life

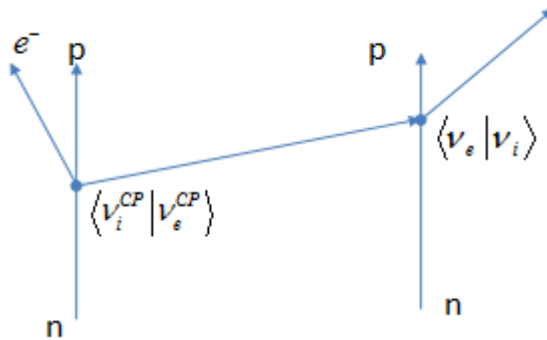
Effective Majorana mass

The mass that can be determined from the half-life of the neutrinoless double beta decay is the so called effective Majorana mass of the neutrino. What is the difference between the Majorana mass term and a normal mass term, for

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^3 |U_{e,i}^2| m_i \cdot e^{i\alpha_i}$$

example measured in single beta decay experiments? The effective Majorana mass term can be written like this:

Where $U_{e,i}$ are the elements of the neutrino mass mixing matrix. The m_i is one of the mass eigenstates and α_i is the so called Majorana phase. The reason why this phase does not cancel out in this term can be easily seen if one looks at the emission and absorption of the neutrinos. The coupling of the flavor eigenstate at



the emission vertex is proportional to $\langle \nu_i^{CP} | \nu_e^{CP} \rangle = \sum_i \langle \nu_i^{CP} | U_{ei}^* | \nu_i^{CP} \rangle = U_{ei}^*$

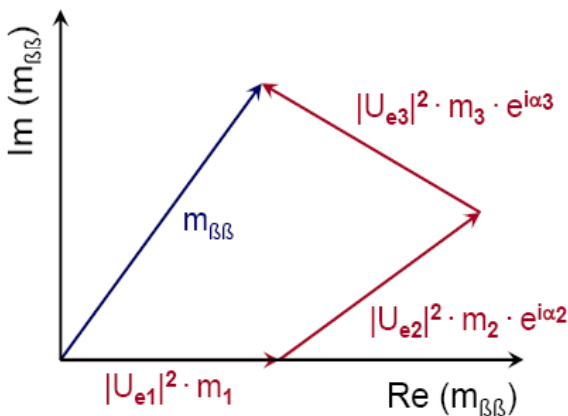
and the coupling of the propagating mass eigenstate to the absorbed flavor eigenstate is proportional to

$$\langle \nu_e | \nu_i \rangle = \langle \nu_i | \nu_e \rangle^\dagger = U_{ei}$$

Since the total amplitude of the neutrinoless beta decay is proportional to

$$\langle m_{\beta\beta} \rangle^2 = \sum_i (U_{ei}^*)^2 m_i$$

the Majorana phase α , which is absorbed in the $U_{e,i}$ term, does not cancel out.



It is a coherent sum over the mass eigenstates where destructive interference is possible. Everything depends on the value of the Majorana phases. The single mass eigenstates could even be larger than $\langle m_{\beta\beta} \rangle$. Because of that only the range of the neutrino mass can be determined by the neutrinoless double beta decay.

Calculate the effective Majorana mass

Weak interaction theory tells us that the effective Majorana mass is to be calculated like this:

$$\langle m_{\beta\beta} \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \cdot G^{0\nu\beta\beta}(E_0, Z) \cdot |M^{0\nu\beta\beta}|^2 \right)^{-1}$$

with $T_{1/2}^{0\nu\beta\beta}$ the experimentally determined half-life. $G^{0\nu\beta\beta}(E_0, Z)$ the phase space factor of the decay and $M^{0\nu\beta\beta}$ the nuclear matrix element. This way of calculating the effective neutrino mass assumes no right-handed weak currents. Due to the virtual character of the neutrino the phase space factor for the neutrinoless double beta decay is much larger than for the two neutrino double beta decay. The computation of the nuclear matrix elements is very difficult and has still an uncertainty of 3, so the Majorana mass depends heavily on the choice of the nuclear matrix computation model.

Experiments

Passive and active target experiments

To measure such a rare event as the double beta decay experimentalists have devised many different setups. The two main classes are passive and active target experiments. Passive target experiments most often have very thin β emitting foils which are placed between detectors. It is quite easy to change the foils, so different isotopes can be measured with the same detectors. A major disadvantage is self absorption in the foils themselves. To avoid this they have to be very thin and this limits the source mass. With active target setups this does not happen because the signal is detected in the source itself.

Semiconductor detector experiments

These experiments use semiconductor diodes, often made from 76-Germanium. They are active target experiments and have a high energy resolution. 76-Germanium has a high natural abundance but unfortunately a low Q-value of 2.04 MeV, which makes it hard to discriminate from the natural radioactivity background and thus needs passive shielding. In recent experiments this solid passive shielding was identified to be itself a large source of radioactivity. Two examples are the Heidelberg-Moscow-Experiments (HDMS) and the next generation experiment Germanium Detector Array (GerDA).

Heidelberg-Moscow-Experiment

It is the first experiment to claim a signal for the neutrinoless double beta decay but the community is skeptic. About 11 kg of enriched Germanium were operated from 1990 until 2003. Set up in 5 diodes these were clad in lead and

copper. The 13 years of measurement are equivalent to 71.7 kg*years of data in which 28.75 ± 6.86 events were detected. The measured half-life is:

$$T_{1/2}^{0\nu\beta\beta} = (0.6 - 4.18) \times 10^{25} \text{ y}$$

this leads to a calculated effective Majorana mass:

$$\langle m_{\beta\beta} \rangle = (0.2 - 0.6) \text{ eV}$$

A big problem of these kinds of experiments is the background simulation and the ability to distinguish γ -events (from natural radioactivity) and β -events which should be solely from the beta decay. Another data analysis method was later used by the Heidelberg-Moscow collaboration: The Pulse Shape Analysis.

Pulse shape analysis

Theory tells us that 90% of all β -events are localized in a small volume in the detector, so called single site events (SSE), whereas normal γ -events are multiple site events (MSE). All events were classified and all identified MSE were excluded from the data analysis. With this procedure 11 ± 1.8 events were detected. With $T_{1/2}^{0\nu\beta\beta} = 2.23_{-0.31}^{+0.44} \times 10^{25} \text{ y}$ and $\langle m_{\beta\beta} \rangle = 0.32_{-0.03}^{+0.03} \text{ eV}$

This means less than one $\beta\beta$ -event per year! It is obvious that one has to increase the sensitivity of the experiments.

Sensitivity increase for next generation experiments

The sensitivity for $T_{1/2}^{0\nu\beta\beta}$ is proportional to $a \sqrt{\frac{Mt}{B\Delta E}}$ with a =isotopic abundance, M =target mass, B =background, ΔE =energy resolution, t =measurement time. An essential step is to enrich the target mass, which makes easy enrichable isotopes the material of choice. The next step is to reduce the background. This is done with low level shielding materials, a radon free environment, detector segmentation, active vetos for μ and neutrons. The μ - and neutron-flux is also reduced by the fact that all these experiments are build in underground laboratories.

In the end it is necessary to increase the target mass, but since the effective Majorana mass is proportional only to the square root of the half-life the increase from about 11 kg(HDMS) to about 1t of target material in envisioned future experiments yields only a three times better sensitivity!

Germanium Detector Array (GerDA)

GerDA is a next generation semiconductor experiment and is currently being setup in the Gran Sasso Underground Laboratory. It is very similar to the HDMS-Experiment; some of the diodes are even recycled! But in contrast to HDMS the diodes are immersed in cryogenic fluid, either liquid nitrogen or liquid argon. This design change removes the background coming from the solid shielding. In the first phase of GerDA the diodes from HDMS are stripped of their copper shielding which will result in a background count of about 0.01 per keV*kg*year and an effective mass sensitivity $\langle m_{\beta\beta} \rangle = 0.3 - 0.9 \text{ eV}$. The second phase will use 35 kg of new segmented germanium diodes. The second phase setup will reduce the background to 0.001 cts/(keV*kg*year) and will allow a sensitivity of about $\langle m_{\beta\beta} \rangle = 0.09 - 0.29 \text{ eV}$. This reduction is mainly achieved by reducing the external γ -background. Segmenting the diodes offers means to detect ionization signals in more than 1-2 segments at the same time and since $\beta\beta$ -events are localized all signal that are seen in more than 1-2 segments are rejected. But this means read-out electronics for each segment, which have to be calibrated, held stable and so forth. The liquid argon anticoincidence works in similar way. When scintillation light in the LAr is detected simultaneously with an assumed $\beta\beta$ -signal this signal is not considered an event because it most likely comes from a natural radioactivity γ .

CUORICINO

CUORICINO uses the bolometer setup with 62 TeO_2 crystals. The crystals are placed in a dilution refrigerator at about 10mK. These bolometers can detect small energy deposits because one makes use of the Debye-law.

$$C(T) \sim \left(\frac{T}{T_D}\right)^3$$

With $T \rightarrow 0$ the temperature change becomes $\Delta T \sim \frac{E}{C(T)}$

An energy deposit of $E=2.53 \text{ MeV}$ (Q-value of Tellurium) would result in $\Delta T=0.18\text{mK}$. This temperature change is read-out via thermistors and superconducting devices that are run near their critical temperature. If the temperature changes just a tiny bit, these devices will lose their superconductivity. In 3 years of measurement a background rate of 0.19 cts/(kg*keV*year) was seen and no evidence for neutrinoless double beta

decay was observed. An upper limit for the half-life $T_{1/2}^{0\nu\beta\beta} > 2.4 \cdot 10^{24}$ y and a lower limit for the effective mass $\langle m_{\beta\beta} \rangle < 0.19 - 0.68 eV$ can be justified.

A third phase is called Cryogenic Underground Observatory for Rare Events (CUORE). In this phase 988 TeO_2 crystals will be used to look for the neutrinoless double beta decay.

Enriched Xenon Observatory (EXO)

EXO uses a Time Projection Chamber (TPC) with either liquid or gaseous Xenon. Xenon is easy to purify and enrich and has Q-value higher than the natural radioactivity. The decay product of Xenon is a two times charged Barium-ion. The spectroscopic properties of the ion are quite well known that makes it possible to tag them with laser. All these properties make Xenon an ideal material for the observation of the neutrinoless double beta decay.

The first phase of EXO, called EXO 200 does not use the ion-tagging method identify the barium-ion. 200 kg of liquid Xenon are filled in a TPC, which uses a combination of scintillation and ionization to achieve an acceptable energy resolution (not good in LXe). Through using the dense LXe in a small volume a good spatial resolution is achieved. Otherwise it will work like a normal TPC.

In the next phase 1t of enriched liquid Xenon or gaseous Xenon will form the target mass. Laser spectroscopic methods can detect single (!!) barium-ions via characteristic absorption lines. This reduces the background from natural radioactivity because the coincidence of the detection of two electrons and a barium-ion means a double beta definitely occurred. But with this method it is not possible to distinguish the two neutrino double beta decay and the neutrinoless double beta decay! This is only possible with a good enough energy resolution which hard to achieve with the liquid xenon target mass.

EXO will also look for the two neutrino double beta decay because it has not been observed yet in xenon. The results will test for the computed nuclear matrix elements. To know the half life of the two neutrino double beta decay is very important for the background estimates of the neutrinoless double beta decay since the two decay leave nearly the same signal. After two years of measurement EXO-200 will be sensitive to an effective neutrino mass of 186

meV. The full scale 1t EXO with 5 years measurement time will achieve about 33 meV.

Current and future neutrinoless double beta experiments

name	target nuclei	mass[kg]	method	laboratory	status
COURICINO	130-Te	40.7	bolometer	Gran Sasso	finished
NEMO-3	100-Mo/82-Se	6.9	tracking calorimeter	Fréjus	taking data
GerDA	76-Ge	15/35/500	semiconductor	Gran Sasso	by 2009/10
EXO	136-Xe	200/1000	TPC/lon tagging	WIPP	by 2009
CUORE	130-Te	750	bolometer	Gran Sasso	2011

Conclusion

As one has seen there is a great variety of approaches to the neutrinoless double beta decay, each with its advantages and disadvantages. Additionally it is probably not enough to have one experiment that observes the neutrinoless double beta decay but at least two are needed. This is why, although the Heidelberg-Moscow experiment claims the observation, many new and ingenious experiments are currently being build.

To observe such a rare event like the neutrinoless double beta decay it has become apparent that large collaborations and a lot of funding is needed to build the necessary large scale experiments.

The neutrino mass scale is very important to cosmology and astrophysics. Together with single beta decay experiments this information will give new insight into the evolution of the universe, galaxy-formation, stars and many more.