Fundamental Neutrinos Properties

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Abstract After about six decades since the discovery of the neutrino, we have started to understand the role of neutrinos in our world. The discoveries of oscillations of atmospheric, solar, accelerator and reactor neutrinos have opened a new excited era in neutrino physics and represents a big step forward in our knowledge of neutrino properties. The observed small neutrino masses have profound implications for our understanding of the Universe and are now a major focus in astro, particle and nuclear physics and in cosmology. The physics community worldwide is embarking on the challenging problem, finding whether neutrinos are indeed Majorana particles (i.e., identical to its own antiparticle) as many particle models suggest or Dirac particles (i.e., is different from its antiparticle). The search for the $0\nu\beta\beta$-decay represents the new frontiers of neutrino physics, allowing to determine the Majorana nature of neutrinos and to fix the neutrino mass scale and possible CP violation effects, which could explain the matter-antimatter asymmetry in the Universe.

1 Introduction

Until the early part of the twentieth century neutrinos were unknown. On 4 December 1930 Wolfgang Pauli postulated a new particle in an attempt not to abandon the energy law and angular momentum conservation in the nuclear beta decay. Enrico Fermi called this new particle the neutrino and incorporated it in his theory of weak interaction.

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Three types or flavor of neutrinos are known. There is strong evidence that no additional neutrinos exist, unless their properties are unexpectedly very different from the known types. According to the charged leptons produced with the neutrinos they are referred to as electron neutrino ν_e, muon neutrino ν_μ, or tau neutrino ν_τ. In the Standard Model of Particle Physics they belong to the family of leptons. The three different neutrinos are complemented by anti-neutrinos, which have the same mass as neutrinos but inverse characteristics. As neutrinos are neutral and carry no charge they can be their own anti-particles (Majorana neutrinos).

Neutrinos are very special particles, which allow unique insights into fundamental questions in particle physics. The symmetries of Standard model of particle physics are associated with total baryon and lepton number and lepton flavor conservation. But, there is no known fundamental principle, which would require this. While massless neutrinos are part of the Standard model, from the observation of neutrino oscillations we now know that at least two neutrino species are massive, i.e. the lepton flavor is violated. Thus, neutrinos constitute direct evidence for physics beyond the Standard model. The smallness of neutrino masses can be explained by the interplay of weak-scale Dirac masses with much larger Majorana masses within the so-called sees-saw mechanism. In this way neutrinos are potentially a window to very high mass scales, directly inaccessible to foreseeable colliders.

There are many open questions about neutrinos that need both theoretical and experimental exploration. The subject of interest is the absolute mass scale, mixing, the Majorana or the Dirac nature of neutrinos, their electromagnetic properties and the possible existence of CP violation in the leptonic sector. A large enough CP violation is necessary to create the asymmetry between matter and anti-matter in the early Universe, and a large CP violation discovery in neutrino oscillations or neutrinoless double beta decay would support the evidence for the role of neutrinos in this mechanism.

The puzzle of absolute mass scale of neutrinos can be solved by the tritium end-point distortion measurement, from the evaluation of large scale structure in the Universe and with next generation of the neutrinoless double beta decay experiments. The question, whether neutrinos and anti-neutrinos are distinct (Dirac particle), or in fact the same particle (Majorana particle) is of great importance. Neutrinoless double beta-decay is the most important source of information about this problem. There is a chance that this process could be observed in the foreseeable future.

From the radioactive decay of atoms to the evolution of the Universe, neutrinos are central to our understanding of particle physics and astrophysics.

2 Sources of Neutrinos

In number, neutrinos exceed the constituents of ordinary matter (electrons, protons, neutrons) by a factor of ten billion. There are about 10^{87} neutrinos per flavor in the visible Universe, which corresponds to the number density per flavor of relic (anti-)neutrinos in average over the Universe about $56\,\mathrm{cm}^{-3}$. They were first created in the Big Bang, in the beginning of the Universe, and continue to be created in nuclear reactions and particle interactions. They travel through the Universe with close to the speed of light.

Relic neutrinos has not yet been confirmed by direct observations due to their small energy. This represents a challenging problem of modern cosmology and experimental astroparticle physics.

The Sun, where intense nuclear reactions are constantly occurring, emits 2×10^{38} electron-neutrinos every second. They have an energy between 0 and 20 MeV, depending of the type of solar nuclear reaction they come. There are about 70 billion neutrinos per square centimeter and second streaming through the Earth from the Sun.

Neutrinos govern the dynamics of supernovae, and hence the production of heavy elements in the Universe. When the mass of the inert core exceeds the Chandrasekhar limit of about 1.4 solar masses, electron degeneracy alone is no longer sufficient to counter gravity. When a massive star at the end of its life collapses to a neutron star, it radiates almost all of its binding energy in the form of neutrinos, most of which have energies in the range 10–30 MeV. These neutrinos come in all flavors, and are emitted over a timescale of several tens of seconds. The total number of neutrinos spewed out by the supernova SN 1987A at Large Magellanic Cloud (distance of 168000 light-years) exceeded 10^{58} while over a period of ten seconds 5×10^{28} of them passed right through the Earth and 24 of them were detected at underground laboratories.

Neutrinos are created in the collision of primary cosmic rays (typically protons) with nuclei in the upper atmosphere of Earth. This creates a shower of hadrons, mostly pions. The pions decay to a muon and a muon neutrino. The muons decay to an electron, another muon neutrino, and an electron neutrino. The averaged energy of atmospheric neutrinos is about few GeV. The first detections of atmospheric neutrinos were made in the early sixties in deep mines by Reines et al. in South Africa. Currently, atmospheric neutrinos with large energy range from hundreds of MeV up to TeV region are detected in various underground (SuperKamiokande), underwater (Baikal experiment, ANTARES, NEMO) experiments and other (IceCube) experiments.

Neutrinos are produced inside nuclear power plants as by-product of nuclear fissions. Nuclear reactors emit about 5×10^{20} antineutrinos per second and per GW of thermal power with a mean energy of 4 MeV. Man-made neutrinos are produced also by using beams of high energy protons generated by large accelerators like the ones at CERN, Fermilab and KEK.

The interior of the Earth is a source of antineutrinos due to natural radioactivity. Radiogenic heat arises mainly from the decay (chains) of ^{238}U, ^{232}Th and ^{40}K. All these elements produce heat together with antineutrinos, with well fixed ratios heat/neutrinos. The geo-neutrinos has been successfully detected for the first by the KamLAND and Borexino experiments. The direct information of the heat generation mechanism obtained by neutrinos means the opening of a new field of science called “Neutrino Geophysics”.

Depending on the source and the environment in which neutrinos are produced, different types of neutrinos are created, and their energies range from 0.0004 eV (Big Bang neutrinos) to 30×10^9 eV, or higher (at accelerators). Because of their weak interaction with other particles, matter is almost completely transparent to neutrinos and large sensitive detectors are needed to capture them.

3 Neutrino Oscillations

Neutrino oscillation is a quantum mechanical phenomenon predicted by Bruno Pontecorvo [1, 2]. He thought that there is an analogy between leptons and hadrons and believed that in the lepton world a phenomenon does exist, which is analogue to the well-known $K^0\,\overline{K}^0$ oscillations. In the neutrino oscillation a neutrino created with a specific lepton flavor (electron, muon or tau) can later be measured to have a different flavor.

Neutrino flavor states $|\nu_\alpha\rangle$ are related to the mass-eigenstates $|\nu_j\rangle$ with masses m_j (j =1, 2, 3) and vice versa by the linear combinations

$$|\nu_\alpha\rangle = \sum_{j=1,2,3} U_{\alpha j}|\nu_j\rangle, \quad |\nu_j\rangle = \sum_{j=1,2,3} U^*_{\alpha j}|\nu_\alpha\rangle, \tag{1}$$

where U is the Pontecorvo-Maki-Nakagawa-Sakata unitary mixing matrix, which can be written as

$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \tag{2}$$

with $c_{ij} \equiv \cos(\theta_{ij})$, $s_{ij} \equiv \sin(\theta_{ij})$. θ_{12}, θ_{13} and θ_{23} and three mixing angles and δ is the CP-violating phase. If neutrinos are Majorana particles U in Eq. (2) is multiplied by a diagonal phase matrix $P = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, e^{i\delta})$, which contains two additional CP-violating Majorana phases α_1 and α_2:

The transition probability of different neutrino species into each other is

$$P_{\alpha\to\beta}(E, L) = \sum_{j=1,2,3}\sum_{k=1,2,3} U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}e^{i\Delta m^2_{kj}L/(2E)} \tag{3}$$

with $c = 1$, $t \approx L$ (distance from source), $\Delta^2_{kj} = m^2_k - m^2_j$. In the two-flavor approximation we get

$$P_{\alpha\to\beta}(E, L) \approx \sin^2(2\theta)\sin^2\left(1.27\Delta m^2_{[eV^2]}L_{[m]}/E_{[MeV]}\right). \tag{4}$$

We note that the probability of measuring a particular flavor for a neutrino varies periodically as it propagates.

Various early measurements of neutrinos produced in the Sun, in the atmosphere, and by accelerators suggested that neutrinos might oscillate from one flavor (electron-, muon-, and tau-) to another expected as a consequence of non-zero neutrino mass. Starting 1998 we have a convincing evidence about the existence of neutrino masses due to SuperKamiokande (atmospheric neutrinos) [3], SNO (solar neutrinos) [4], KamLAND (reactor neutrinos) [5], MINOS (accelerator neutrinos) and other experiments. Neutrinos produced in the atmosphere arrived at the Super-Kamiokande detector from distances of about 40 km (if produced above it) to 12,000 km (if produced on the other side of the Earth). In accordance with theory of neutrino oscillations data were found to be dependent on the zenith angle. The neutrinos from accelerators or nuclear reactors on Earth were detected at significantly smaller distances. The behavior of neutrinos produced over a great distance at the Sun allows us observe effects, which would be invisible with a closer source. We note also that data agree well with the oscillation hypothesis regardless of energy.

With the discovery of neutrino oscillations quite a lot of information regarding the neutrino sector has become available. More specifically we know:

- The mixing angles θ_{12} and θ_{23}, which are large, and we have both a lower and an upper bound on the small angle θ_{13}.
- We know the mass squared differences:

$$\Delta^2_{\text{SUN}} = \Delta^2_{12} = m_2^2 - m_1^2, \quad \text{and } \Delta^2_{\text{ATM}} = |\Delta^2_{23}| = |m_3^2 - m_2^2|$$

  entering the solar and atmospheric neutrino oscillation experiments. Note that we do not know the absolute scale of the neutrino mass and the sign of Δ^2_{23}.

Currently, the neutrino oscillation parameters are as follows: The MINOS value $\Delta m^2_{\text{ATM}} = (2.43 \pm 0.13) \times 10^{-3}\text{eV}^2$ [6], the global fit values $\Delta m^2_{\text{SUN}} = (7.65^{+0.13}_{-0.20}) \times 10^{-5}\text{eV}^2$ and $\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$ [7], the solar-KamLAND value $\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$ [5] and the recent T2K and DOUBLE CHOOZ observations θ_{13}: $0.04 < \sin^2 2\theta_{13} < 0.34$ [8]. $\sin^2(2\theta_{13}) = 0.085 \pm 0.029(stat) \pm 0.042(syst)$ (68 % CL) [9].

4 The Elusive Absolute Scale of the Neutrino Mass

At present the structure of the neutrino mass spectrum is not known. There are two possible scenarios:

- Normal Spectrum (NS), $m_1 < m_2 < m_3$:

$$m_0 = m_1,\; m_2 = \sqrt{\Delta m^2_{\text{SUN}} + m_0^2}\,,\; m_3 = \sqrt{\Delta m^2_{\text{ATM}} + m_0^2},$$

with $\Delta m^2_{\rm SUN} = m_2^2 - m_1^2$ and $\Delta m^2_{\rm ATM} = m_3^2 - m_1^2$.

- Inverted Spectrum (IS), $m_3 < m_1 < m_2$:

$$m_0 = m_3, m_2 = \sqrt{\Delta m^2_{\rm ATM} + m_0^2}, m_1 = \sqrt{\Delta m^2_{\rm ATM} - \Delta m^2_{\rm SUN} + m_0^2}$$

with $\Delta m^2_{\rm SUN} = m_2^2 - m_1^2$ and $\Delta m^2_{\rm ATM} = m_2^2 - m_3^2$.

Here, $m_0 = m_1(m_3)$ is the lightest neutrino mass for NS (IS).

The absolute scale m_0 of neutrino mass can in principle be determined by the following observations:

- Neutrinoless double beta decay.

As we shall see later (Sect. 5) the effective Majorana neutrino mass $m_{\beta\beta}$ extracted in such experiments is given as follows:

$$m_{\beta\beta} = \sum_k^3 U_{ek}^2 m_k = c_{12}^2 c_{13}^2 e^{2i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\alpha_2} m_2 + s_{13}^2 m_3. \quad (5)$$

- The neutrino mass extracted from ordinary beta decay, e.g. from tritium β-decay [10].

$$m_\beta = \sqrt{\sum_k^3 |U_{ek}|^2 m_k^2} = \sqrt{c_{12}^2 c_{13}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}. \quad (6)$$

assuming, of course, that the three neutrino states cannot be resolved.

- From astrophysical and cosmological observations (see, e.g., the recent summary [11]).

$$m_{\rm astro} = \sum_k^3 m_k. \quad (7)$$

The current limit on $m_{\rm astro}$ depends on the type of observation[11]. Thus CMB primordial gives 1.3 eV, CMB+distance 0.58 eV, galaxy distribution and lensing of galaxies 0.6 eV. On the other hand the largest photometric red shift survey yields 0.28 eV [12]. For purposes of illustration we will take a world average of $m_{\rm astro} =$ 0.71 eV.

The above results are exhibited in Fig. 1 for the tritium β-decay and cosmological limits as a function of the lowest neutrino mass and in Fig. 2 for the case of the $0\nu\beta\beta$-decay both for the NS and the IS scenarios. The allowed range values of $|m_{\beta\beta}|$ as a function of the lowest mass eigenstate m_0 is exhibited. For the values of the parameter $\sin^2 2\theta_{13}$ new Double Chooz data are used [9]. The IH allowed region for $|m_{\beta\beta}|$ is presented by the region between two parallel lines in the upper part of Fig. 2. The NH allowed region for $|m_{\beta\beta}| \approx$ few meV is compatible with m_0 smaller than 10 meV. The quasi-degenerate spectrum can be determined, if m_0 is known from future β-decay experiments KATRIN and MARE [10] or from cosmological observations.

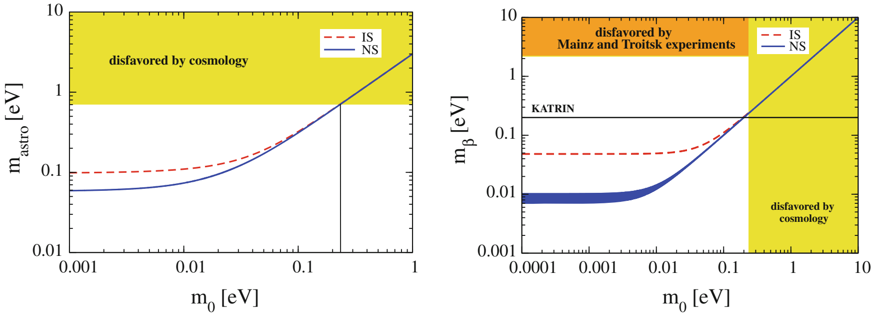

Fig. 1 The neutrino mass limits in eV as a function of mass of the lowest eigenstate m_0 also in eV, extracted from cosmology (*left panel*) tritium β-decay (*right panel*). From the current upper limit of 2.2 eV of the Mainz and Troitsk experiments we deduce a lowest neutrino mass of 2.2 eV both for the NS and IS. From the astrophysical limit value of 0.71 eV the corresponding neutrino mass extracted is about 0.23 eV for the NS and IS

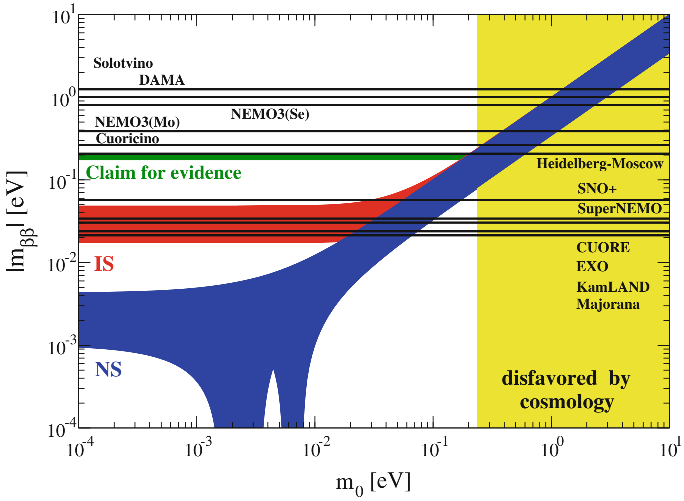

Fig. 2 We show the allowed range of values for $|m_{\beta\beta}|$ as a function of the lowest mass eigenstate m_0 using the three standard neutrinos for the cases of normal (NS, $m_0 = m_1$) and inverted (IS, $m_0 = m_3$) spectrum of neutrino masses. Also shown are the current experimental limits and the expected future results [13] (QRPA NMEs with CD-Bonn short-range correlations and $g_A = 1.25$ are assumed [14]). Note that in the inverted hierarchy there is a lower bound, which means that in such a scenario the $0\nu\beta\beta$-decay should definitely be observed, if the experiments reach the required level. The same set of neutrino oscillation parameters as in Fig. 1 is considered

The lowest value for the sum of the neutrino masses, which can be reached in future cosmological measurements [12], is about (0.05–0.1) eV. The corresponding values of m_0 are in the region, where the IS and the NS predictions for m_β differ significantly from each other.

5 Neutrinoless Double-Beta Decay and Double-Electron Capture

Investigations of neutrino oscillations in vacuum and in matter do not allow to distinguish massive Dirac from massive Majorana neutrinos. In order to reveal the Majorana nature of neutrinos is necessary to study processes in which the total lepton number is violated. The best sensitivity on small Majorana neutrino masses can be reached in the investigation of neutrinoless double-beta decay ($0\nu\beta\beta$-decay),

$$(A, Z) \rightarrow (A, Z+2) + 2e^-, \tag{8}$$

and the resonant neutrinoless double-electron capture (0νECEC)

$$e_b^- + e_b^- + (A, Z) \rightarrow (A, Z-2)^{**}. \tag{9}$$

A double asterisk in Eq. (9) means that, in general, the final atom $(A, Z-2)$ is excited with respect to both the electron shell, due to formation of two vacancies for the electrons, and the nucleus.

There are few tenths of nuclear systems [15], which offer an opportunity to study the $0\nu\beta\beta$-decay and the most favorable are those with a large $Q_{\beta\beta}$-value. Neutrinoless double beta decay has not yet been confirmed. The strongest limits on the half-life $T^{0\nu}_{1/2}$ of the $0\nu\beta\beta$-decay were set in Heidelberg-Moscow (^{76}Ge, 1.9×10^{25} y), [16], NEMO3 (^{100}Mo, 1.0×10^{24} y) [17], CUORICINO (^{130}Te, 3.0×10^{24} y) [18] and KamLAND-Zen (^{136}Xe, 5.7×10^{24} y) [19] experiments. There exist, however, a claim of the observation of the $0\nu\beta\beta$-decay of ^{76}Ge made by some participants of the Heidelberg-Moscow collaboration [20] with half-life $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ years. This result will be checked by an independent experiment relatively soon. In the new germanium experiment GERDA [21], the Heidelberg-Moscow sensitivity will be reached in about one year of measuring time.

The inverse value of the $0\nu\beta\beta$-decay half-life for a given isotope (A,Z) is given by

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2|m_{\beta\beta}|^2.$$

Here, $G_{0\nu}(Q_{\beta\beta}, Z)$ and $|M^{0\nu}|$ are, respectively, the known phase-space factor and the nuclear matrix element, which depends on the nuclear structure of the particular isotope under study.

The main aim of experiments on the search for $0\nu\beta\beta$-decay is the measurement of the effective Majorana neutrino mass $m_{\beta\beta}$. From the most precise experiments on the search for $0\nu\beta\beta$-decay [16, 18, 19] by using of nuclear matrix elements of Ref. [14] the following stringent bounds were inferred

$$\begin{aligned}|m_{\beta\beta}| &< (0.20-0.32)\text{eV}\,(^{76}\text{Ge}),\\ &< (0.33-0.46)\text{eV}\,(^{130}\text{Te}),\\ &< (0.17-0.30)\text{eV}\,(^{136}\text{Xe}).\end{aligned} \tag{10}$$

In future experiments, CUORE (^{130}Te), EXO, KamLAND-Zen (^{136}Xe), MAJORANA (^{76}Ge), SuperNEMO (^{82}Se), SNO+ (^{150}Nd), and others [22], a sensitivity

$$|m_{\beta\beta}| \simeq \text{a few}10^{-2}\text{eV} \tag{11}$$

is planned to be reached, what is the region of the IH of neutrino masses. In the case of the normal mass hierarchy $|m_{\beta\beta}|$ is too small in order to be probed in the $0\nu\beta\beta$-decay experiments of the next generation.

The mere observation of the resonant 0νECEC could also prove the Majorana nature of neutrinos as well as the violation of the total lepton number conservation. Recently, a new theoretical framework for the calculation of resonant 0νECEC transitions, namely the oscillation of stable and quasi-stationary atoms due to weak interaction with violation of the total lepton number and parity, was proposed in [23, 24].

The 0νECEC transition rate near the resonance is of Breit-Wigner form,

$$\Gamma_{ab}^{0\nu\text{ECEC}}(J^\pi) = \frac{|V_{ab}(J^\pi)|^2}{\Delta^2+\frac{1}{4}\Gamma_{ab}^2}\Gamma_{ab}, \tag{12}$$

where J^π denotes angular momentum and parity of final nucleus. The degeneracy parameter can be expressed as $\Delta = Q - B_{ab} - E_\gamma$. Q stands for a difference between the initial and final atomic masses in ground states and E_γ is an excitation energy of the daughter nucleus. $B_{ab} = E_a + E_b + E_C$ is the energy of two electron holes, whose quantum numbers (n, j, l) are denoted by indices a and b and E_C is the interaction energy of the two holes. The binding energies of single electron holes E_a are known with accuracy with few eV. The width of the excited final atom with the electron holes is given by

$$\Gamma_{ab} = \Gamma_a + \Gamma_b + \Gamma^*. \tag{13}$$

Here, $\Gamma_{a,b}$ is one-hole atomic width and Γ^* is the de-excitation width of daughter nucleus, which can be neglected. Numerical values of Γ_{ab} are about up to few tens eV.

For a capture of $s_{1/2}$ and $p_{1/2}$ electrons the explicit form of lepton number violating amplitude associated with nuclear transitions $0^+ \to J^\pi = 0^\pm, 1^\pm$ is given in [24]. By factorizing the electron shell structure and nuclear matrix element one gets

$$V_{ab}(J^\pi) = \frac{1}{4\pi}G_\beta^2 m_{\beta\beta}\frac{g_A^2}{R}\langle F_{ab}\rangle M^{0\nu ECEC}(J^\pi). \tag{14}$$

Here, $\langle F_{ab} \rangle$ is a combination of averaged upper and lower bispinor components of the atomic electron wave functions [24] and $M^{0\nu ECEC}(J^{\pi})$ is the nuclear matrix element. R is the nuclear radius and g_A is the axial-vector coupling constant.

In the unitary limit some 0νECEC half-lives were predicted to be significantly below the $0\nu\beta\beta$-decay half-lives for the same value of $m_{\beta\beta}$.

6 Conclusion

As the most intriguing and fascinating fundamental particle, the neutrino is so important that neutrino physics has become one of the most significant branches of modern physics. If we are to understand 'why we are here' and the basic nature of the Universe in which we live, we must understand the basic properties of the neutrino. Once the fundamental properties of neutrinos became clear, neutrinos can be used to study various mechanisms in nature. We note that there is no place in the world that cannot be reached by neutrinos.

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