FEATURE

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Research Area: Experimental Physics

KamLAND-Zen Project

Dirac or Majorana?

The average neutrino density is about 300/cm^3 and it is the most abundant known matter particle in the universe. It rarely interacts and thus it is not very familiar in our daily lives. It also took a long time to investigate its properties for the same reason. Its root is the theoretical invention by Pauli in 1930 for explaining the energy and angular momentum conservation in beta decays. Neutrino is the first particle which is theoretically introduced before an experimental discovery. The Majorana neutrino hypothesis, the main subject of this article, already appeared in 1937, but it is not established or excluded yet. Even after the successful observation of neutrinos, it always puzzled researchers with the solar neutrino problem, the atmospheric neutrino anomaly, and so on. These problems have been solved in several years after 1998 through the observations of neutrino oscillations. The studies of the neutrino oscillation in which neutrinos change their kinds during their propagation have extensively developed the understating of neutrino properties such as neutrino flavor mixing and squared mass differences. An experiment, KamLAND, has also contributed and measured the parameter Δm^2_{21} at a precision of 2.6% using the reactor anti-neutrinos. Neutrino oscillation is the definite evidence of the mass of neutrinos and it requires a theoretical framework beyond the standard theory of particles in which the neutrino mass is assumed to be zero. At the same time, the upper limits of neutrino mass provided by cosmological observations and beta decay experiments showed a significantly lighter mass of neutrinos than that of quarks and the other leptons. Neutrino mass confronts a big problem in two meanings, finite but extraordinary light mass. Moreover, only left-handed (rotating to the left) neutrino and right-handed anti-neutrinos are found so far, in spite of the fact that the rotational direction of the massive (slower than light speed) particle changes in the faster coordinate system, as special relativity states. Thus, the right-handed state of neutrinos and left-handed state of anti-neutrinos must be considered as the neutrino oscillation measurements established masses of neutrinos. Charged particles and anti-particles are apparently distinguishable as their charges are opposite. On the contrary, neutral neutrinos have two choices for their relation between neutrinos and anti-neutrinos. One is the Dirac neutrino and another is the Majorana neutrino. If neutrinos are Dirac particles that are the same as charged particles, the undiscovered right-handed neutrino should have the same mass with the known left-handed neutrino and its interaction should be considered to be much

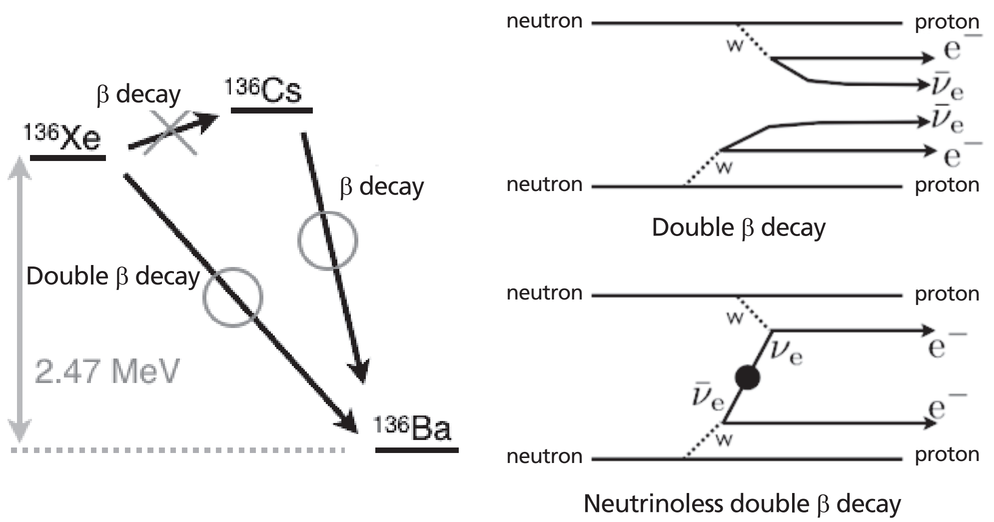

Figure 1. Left: Energy level of a double-beta decay nucleus. Right: Feynman diagrams of double beta decay and neutrinoless double beta decay.

smaller than ordinary neutrinos. It is also known that a particle and its anti-particle have the same mass. Consequently, four states of neutrinos (particle, anti-particle and right-, left-handed for each of them) should have the same mass. On the other hand, the Majorana neutrino doesn't distinguish neutrinos and anti-neutrinos other than their rotational directions and a right-handed neutrino means a right-handed anti-neutrino. In this case, we can separately define a right-handed neutral particle with different mass in the same category. In a so-called *Seesaw model*, a very heavy right-handed "neutrino" at the mass scale close to the grand unified theory is introduced and it explains why ordinary neutrinos are so light. The Majorana nature of neutrinos also includes an apparent violation of B-L (difference of baryon number B and lepton number L) which is necessary for explaining the matter domination of the universe. And the heavy light-handed neutrino introduced in the Seesaw model may also play an important role in creating a non-zero baryon number of the universe through its decay in the early universe as actively discussed with *Leptogenesis theory*.

Neutrinoless double beta decay

Despite the fact that the Majorana nature of neutrinos is a key to addressing the big open questions of cosmology and particle physics, "matter dominance in the universe" and "light neutrino mass," concrete examination has not been achieved. A naïve way would be to look for anti-neutrino interaction by shooting neutrinos, for example. It is not feasible, however, because the fraction of alternative helicity is only about $1/2(m/E)^2$, whereas we know mass is very small and energy should be high to gain the interaction cross section. Luckily, there is one good system in nature. The so-called double beta decay nuclei with which single beta decay is energetically forbidden can go to two

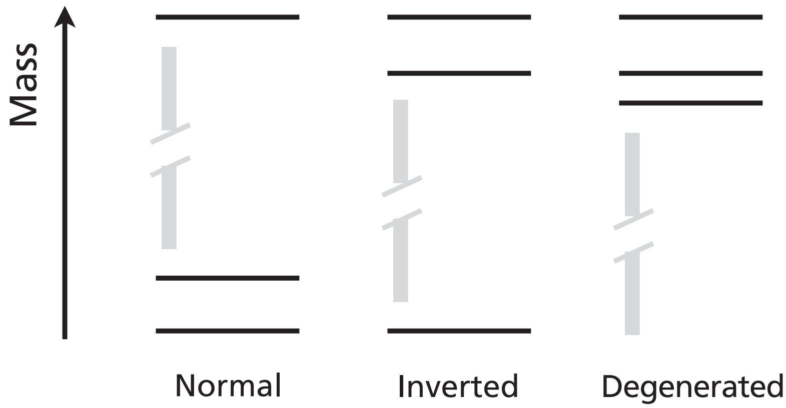

Figure 2: Possibilities of three neutrino mass hierarchies. There are three types of neutrinos, electron neutrino (ν_e), muon neutrino (ν_μ), and tau neutrino (ν_τ). From the results of neutrino oscillation experiments, they are known to be linear combinations of the three mass eigenstates, ν_1, ν_2, and ν_3, which have definite masses m_1, m_2, and m_3, respectively. Though the absolute values of m_1, m_2, and m_3 are yet unknown, $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{32}^2 = | m_3^2 - m_2^2 |$ have been measured by neutrino oscillation experiments, indicating the three possible relations between the neutrino masses m_1, m_2, and m_3: normal ($m_1 < m_2 \ll m_3$), inverted ($m_3 \ll m_1 < m_2$), and degenerated ($m_1 \approx m_2 \approx m_3$) hierarchies.

simultaneous beta decays. In the nucleus, two anti-neutrinos are created in the very small region, and they can annihilate only if neutrinos are massive Majorana particles (see Fig. 1). The annihilation probability is proportional to the squared neutrino effective mass under a popular assumption that light Majorana neutrino exchange dominates the reaction. Thus, the discovery of neutrinoless double beta decay ($0\nu2\beta$ hereafter) is evidence of a Majorana neutrino and also that an effective neutrino mass can be derived from its decay rate. This is so far the only feasible method to investigate the Majorana nature. In spite of the vigorous searches motivated by its physical importance, there is no established evidence for $0\nu2\beta$ except for the one (KKDC claim) with ^{76}Ge nuclei, which claims an effective neutrino mass of about 320 meV at 6σ confidence level. However, possible background candidates and a strange behavior of the signal are argued and further investigation is still necessary. On the other hand, precise measurement of neutrino oscillation provided three possibilities of a three-neutrino-mass hierarchy, *degenerated*, *inverted*, and *normal* hierarchies (see Fig.2). And the effective neutrino mass ranges > 60 meV, 20 – 60 meV and < 20 meV in the three hierarchies, respectively. Based on the possibilities, recent major projects are designed to have sensitivities well below the KKDC claim, to cover the degenerated mass hierarchy, and also to have the potential for an extension to cover the inverted hierarchy. In order to investigate a lifetime of $10^{26\text{-}28}$ years for such targets, it is necessary to contain 100 – 1000 kg of double beta decay nuclei which is much more massive than the previous experiments with only up to about 10 kg.

KamLAND-Zen

Searching for rare phenomena with massive target nuclei is a method common to a proton decay search and neutrino observation. Considering the Q-value of double beta decay is only up to

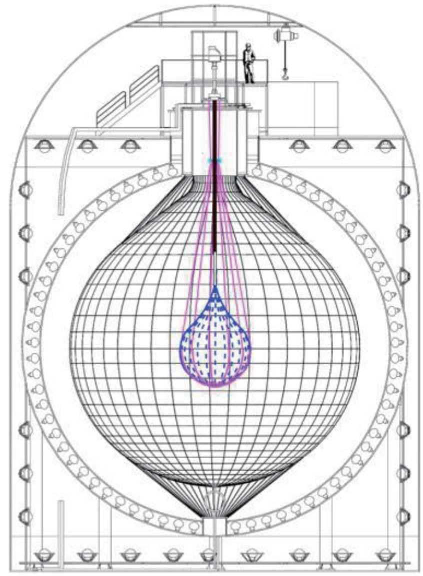

Figure 3: A schematic of the KamLAND-Zen detector.

4.3MeV, the search should also have a feature of ultra-low radioactive impurities. KamLAND detects low energy anti-neutrinos with 1,000 tons of ultra-low-background liquid scintillator (LS) and such an environment is adequate for the $0\nu2\beta$ search. In order to maximize the feature, deployment of unnecessary material in the detector should be avoided. Among various double beta decay nuclei, Xenon-136 (^{136}Xe) is soluble in the LS up to 3wt% and centrifugal isotopic enrichment and purification methods are well established. The Q-value of ^{136}Xe is 2.476 MeV and is not the highest energy. But the problematic background candidates with high-Q nuclei, ^{214}Bi and ^{212}Bi, can be rejected by delayed coincidence with $^{214,212}Po$. KamLAND as a big active shield captures entire signature from ^{208}Tl, 2.615 MeV and 0.583 MeV gammas and additional beta, and the total energy from ^{208}Tl decay becomes much higher than that of $0\nu2\beta$ signals. The other worrisome backgrounds are cosmogenic ^{10}C, solar neutrinos, and ordinary double beta decays ($2\nu2\beta$). The former two are proportional to the target volume and dissolving isotopically enriched ^{136}Xe at the highest concentration is effective. In order to reduce $2\nu2\beta$ backgrounds, energy resolution should be improved. But the light yield of the xenon-loaded LS cannot be increased independently with KamLAND LS in order to have uniform energy response around the boundary.

Under these considerations, it was decided to suspend a mini-balloon containing ^{136}Xe-LS (enriched from natural abundance of 8.9% to more than 90%), see Fig. 3. Its light yield is adjusted with the KamLAND LS and also the density is controlled to slightly heavier than the KamLAND LS in order that the mini-balloon does not float nor receive stress. The balloon film is very thin, 25μm, in order to minimize radioactive impurities in the material and in order to increase the efficiency to detect alphas from Bi-Po sequential decays. Production and installation of the mini-balloon become difficult by using the thin balloon. The new dead-time-

Figure 4. The logo of the KamLAND-Zen project. A kanji, logographic Chinese character, indicating 'Zen' is surrounded by alphabetical characters.

free electronics with 1 GHz flash ADC is used for tagging muon-neutron-^{10}C coincidence where ^{10}C backgrounds accompany neutrons at more than 90% when created from ^{12}C by muon spallation.

The project is designed to cover the degenerated hierarchy first and later modified to cover the inverted hierarchy. In order to cover the degenerated hierarchy in two years, it turned out by a simulation study that about 400 kg of ^{136}Xe is necessary but light yield of KamLAND is good enough. At the time of the design stage, $2\nu2\beta$ half life was known to be very long, more than 10^{22} years, and only moderate energy resolution was required. It was rather shocking when the EXO-200 experiment in the United States reported that the $2\nu2\beta$ half life is 2.11×10^{21} years (factor five contradiction!). Luckily the impact was not very big. For covering the degenerated hierarchy, 3 to 4 years of data accumulation is necessary or the sensitivity with two years became about 80 meV. Anyway, demand for the better energy resolution became stronger.

We named the project as KamLAND-Zen. Zen primarily stands for Zero neutrino double beta decay search. It also contains the sound and meaning of "then" and "Xenon." And searching for a truth of the universe ($0\nu2\beta$) at nothingness (ultra-low background environment) just matches with the word *Zen* (see Fig.4). The experiment started in September with about 330 kg of Xenon and we are expecting to publish a result shortly.

Future plans

Better sensitivity requires more light-yields. But replacement of the KamLAND LS is a big and costly effort. So, we are going to attach light concentrators to PMTs at the same time (see Fig. 5). We expect 2.5 times more light combining with the LS replacement, and $2\nu2\beta$ will be suppressed by a factor of more than 10. The upper entrance will also be enlarged to deploy various instruments. Once $0\nu2\beta$ is found, measurements with higher statistics and different nuclei become important for reducing uncertainty from a theoretical calculation of the nuclear matrix element and for identification of underlying physics mechanisms. Also, a direct search for dark matter

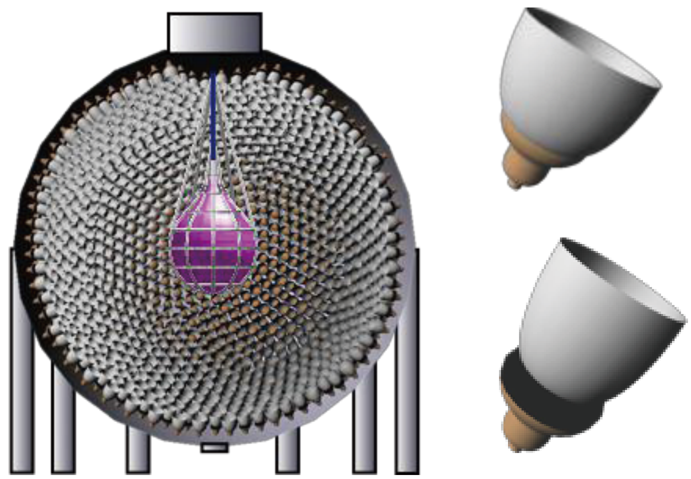

Figure 5. Schematic of the KamLAND2-Zen detector (left) and photomultipliers with light concentrators (right).

with NaI, for example, will become possible. This future upgrade is called as KamLAND2-Zen, and initially KamLAND2-Zen is planned to contain 1,000 kg of enriched ^{136}Xe which will be dissolved in the LS at 80% higher concentration by pressurizing Xenon up to 1.8 bar (balances with 10 m LS depth). The expected sensitivity is about 20 meV, covering the inverted hierarchy.

Some challenging developments are also going on. Scintillating film, for example, will be effective to improve the BiPo tagging efficiency in the mini-balloon, and an imaging device will be useful to distinguish multi-vertexes events such as ^{10}C and multi-compton gamma rays. Employing these technologies, it may be possible to access the normal hierarchy. Among these future plans, pressurizing Xenon is cost effective and an intermediate phase with 800 kg of Xenon before KamLAND2-Zen is considered. Currently, 450 kg of Xenon is in hand and additional procurement is going on. The estimated sensitivity with this phase is about 30 – 40 meV, in the middle of the inverted hierarchy.

Closing

Rapid growth in neutrino research has created a very special observational environment. The ultra-low radioactivity environment established at a huge underground cavity, with ultra clean materials, are developing a new research field of rare phenomena search. The target mass of the double beta decay study has already exceeded 300 kg; it was only up to 10 kg just a few years ago. By using an existing apparatus, the project can keep costs down and have very high scalability. The start-up time can be also reduced. For a detailed study, measurements with various nuclei and of angular distribution are necessary. But such high technology apparatuses often become expensive and single purpose. For the continuous growth of research, a strategy of starting and finding with a general-purpose detector at first and then deepening the research with a dedicated detector seems to be beneficial.