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Future Outlook: Experiment

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Abstract. The personal view for the next to the next neutrino detector, the ultimate experiment, is discussed. Considering the size, cost and head winds against the basic science, the ultimate experiment will be the only experiment in the world. Here two such experiments one for the neutrino oscillation and the other for the double beta decay were discussed. The ultimate experiment needs to include a bread and butter science and to have a discovery potential for an unexpected phenomenon. There are many technical challenges and international co-operations are absolutely necessary.

1. Preface

In 1998, the Super-Kamiokande Collaboration presented an evidence of neutrino oscillation in the study of the atmospheric neutrinos [1]. This discovery was a breakthrough and has opened up new window to theories beyond the standard model of the elementary particle physics and has made a big change in experimental neutrino physics. This year, 2008, is therefore the 10th anniversary of the discovery of the neutrino oscillation.

The story started in 1988 by an atmospheric neutrino anomaly observed in Kamiokande where the measured atmospheric ν_μ flux was about 60% of that expected [2]. The atmospheric neutrino events were at that time one of the major backgrounds for proton decay search in large underground detectors. Since the Kamiokande result was statistically not sufficient and depended on neutrino flux calculations, the effect was not widely accepted though the most favored interpretation was a neutrino oscillation. And the large mixing of the neutrino sector as suggested from the neutrino oscillation interpretation was not a favored scenario for many of the theorists of the time. The Super-Kamiokande experiment started to take data in 1996, soon observed the distance dependent oscillation effect in the zenith angle distribution. This measurement has provided a high statistic, flux independent and compelling evidence for the neutrino oscillation. It took 10 years to establish the phenomena as a real oscillation effect.

The solar neutrino problem, an indication of the deficit of the observed solar neutrino flux in early 70s by the Homestake experiment lead by R. Davis [3], took more than 30 years to be proved as a result of neutrino oscillation. The conclusive evidence was obtained in 2001 by comparing the charged current measurement by SNO and the high statistic neutrino electron scattering of Super-Kamiokande [4]. The result of this comparison provided a flux calculation independent evidence of non-electron neutrino contamination in the solar neutrinos measured on earth. Again this evidence was obtained by the high statistic experiments.

We, at 10 years after the discovery of the neutrino oscillation, have now very well motivated directions towards future neutrino experiments. The comparison the number of talks on each subject given at NEUTRINO98 [5] and at NEUTRINO2008 is shown in figure 1, which reveals the drastic change of interests. There are more interests in long-baseline reactor and accelerator experiments and high energy neutrinos, and less interest in solar, atmospheric neutrinos and short baseline reactor experiments. Others are more or less same though double beta decay and dark matter search should have more entries in my personal opinion.

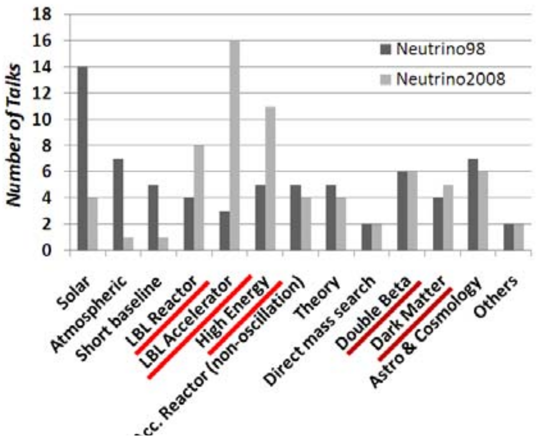

Figure 1. The number of talks given at Neutrino98 [5] and at Netrino2008. The talks on solar and atmospheric neutrinos have decreased, on the other hand those on long-baseline accelerator and reactor experiments have increased.

The discussion we will make here is neither a summary of the experimental part of this conference nor a general view in future, but is quite a biased personal opinion for the direction of future large scale neutrino experiments. For these future experiments, we do not mean the next generation experiments, but think the next to the next generation neutrino experiments. We may call this as an ultimate experiment that may take more than 20 years to be realized.

The ultimate detector presented here was not quantitatively discussed and may be a dream and may not be realistic in the end. This kind of discussion may not fit to the outlook talk and the last talk of the conference. But I am pleased if this discussion will become useful for some of the audience when they think about neutrino experiments 20 or 30 years from now.

2. Standard scenario and ultimate experiments

After the establishment of the neutrino oscillation, we now have a well motivated standard menu for future neutrino experiments. We have many questions to be answered experimentally; is CP violated in neutrino sector, is neutrino Majorana or Dirac, does neutrino has normal or inverted mass hierarchy. And there are yet undetermined parameters which need to be measured, like θ_{13}, CP phase, Majorana mass and so on. Many papers on these subjects were presented in this conference and you can refer those papers if needed.

The ultimate experiments, the next to the next experiments need to cover the standard list as much as possible, but must include other scientific possibilities, or new opportunities, and especially they must have a MEASUREMENT, a bread and butter science, in addition to look for something. We have strong reasons for that: 1) θ_{13}, for example, may not be determined positively within an experimental sensitivity and double beta decay may be out of our accessible range and so on; 2) we will build a huge detector and spend big amount of money with large number of scientists, and then the ultimate experiment may be the only experiment in the world. Therefore a definitive out-come is necessary and we cannot say we have failed to discover any or cannot find any.

We also note that those standard subjects are of importance, but there are no big PUZZLES or problems like once solar and atmospheric neutrino problems. Though we are guided to the promising and fruitful future, we are in the different situation comparing to those days before the discovery of neutrino oscillations. We probably need to be keen to find unexpected and therefore you require to build very good versatile detectors.

The discussion here was limited to two cases for the ultimate experiments, because of the page limitations: 1) neutrino oscillation experiment, and 2) double beta decay experiment

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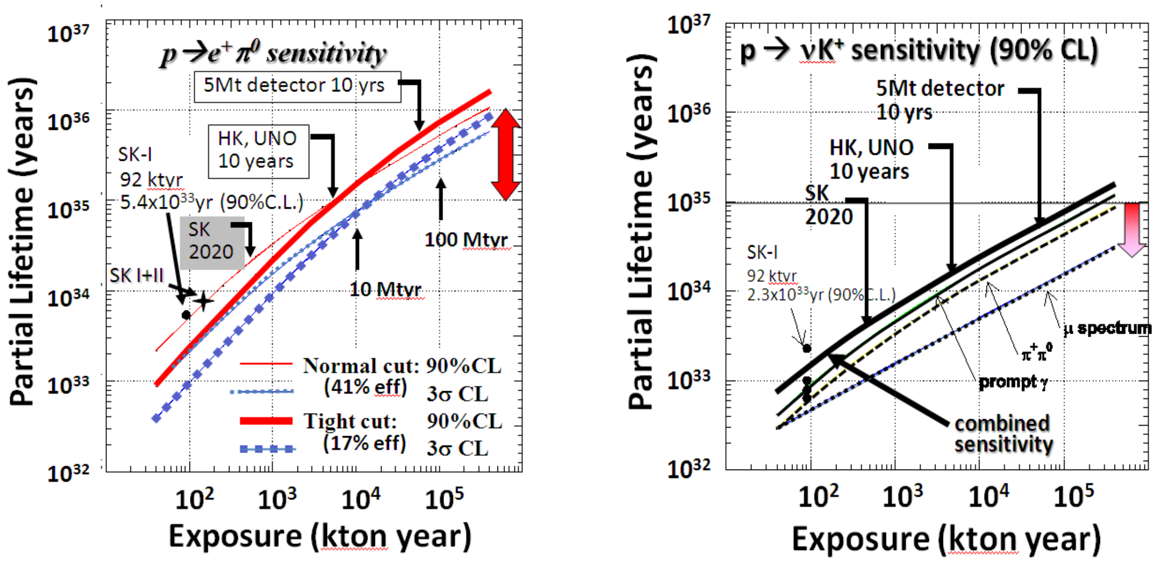

Figure 2. The sensitivity of a 5Mt detector for proton decay. Left panel shows the sensitivity for $p \rightarrow e^+p^0$ mode and right panel shows νK^+ mode. The detector with 5 Mt fiducial mass can explore the proton lifetime between 10^{35}~10^{36} yrs for $e^+\pi^0$ mode and up to 10^{35} yrs for νK^+ mode. Significant improvement would be made for the proton decay search.

3. Ultimate Neutrino Oscillation Experiments

The standard next generation neutrino oscillation experiments aim to study CPV, mass hierarchy and so on with megaton scale detectors with upgraded accelerator powers. The typical detector fiducial mass is 0.54 Mton for a propose hyper-Kamiokande [6] and 0.44 Mton for UNO [7] and similar weight for a European project of MEMPYS[8]. These detectors also have sensitivities for proton decay of $e\pi^0$ mode to 10^{35} yr and more than 100 thousands neutrino events for a Galactic supernova at 10kpc distance. But in some sense, these sensitivities may not be strong enough. In order to strengthen other scientific opportunities, let us consider here a 5 Mt fiducial volume detector as an ultimate experiment.

3.1. Proton decay [9]

One of the discovery potential for the ultimate neutrino oscillation detector is proton decay. The prediction for the partial lifetimes of protons for νK and μK mode is strong model dependent. Therefore you cannot rely on theorists' predictions for νK and μK to determine the size of the detector. However, the prediction from the dimension 6 operator in SUSY GUT is less model dependent and gives reasonable range of 10^{35}~10^{36} yrs for $e\pi^0$ simply from the argument of coupling unification. Therefore the searches up to ~10^{36} yrs for $e\pi^0$ search are quite important and the discovery potential is very high, which add significant value to the experiment. Now the sensitivity for $p \rightarrow e\pi^0$ will guide the size of the experiment.

If you build 5Mt fiducial mass detector and operate 10 yrs, then you can reach ~7×10^{35} yrs whereas the 0.5Mt detector reaches only up to ~1×10^{35} yrs for 10 yrs operation as shown in the left panel in figure 2. By the 25 yrs of operation of Super-Kamiokande most likely to happen in ~2020, the sensitivity will reach to 3×10^{34} yrs (0.5Mtyr exposure). The 0.5Mt detector can improve the SK sensitivity only factor of 3 after the 10 yrs of operation. For the proton decay search, you definitely need a size of multi-Mega ton or need to build a scalable detector.

The situation for νK mode is shown in the right panel in figure 2. Although the νK mode has strong model dependence, νK is important and used to constrain models once you find the proton decay in $e\pi^0$ mode. You can expect to have sensitivity to ~7×10^{34} yrs for 10yrs running time of 5Mt detector. If the detector is scalable, then you can continue to study the sensitive region.

3.2. A bread and butter science for multi-Megaton detectors

Do we have a bread and butter science for a 5Mt detector? Obviously atmospheric neutrinos are one such subject, see talk in these proceedings by A. Smirnov [10]. The precise measurements of the atmospheric neutrinos can map out the matter effect through the earth – Oscillograms. And the detailed study on CP violation, θ_{13} and octant of θ_{23} is possible [9]. But do you have others. The answer is yes. We can detect neutrino bursts even from supernovae from 5Mpc distance, which gives you one supernova neutrino burst detected every year [11].

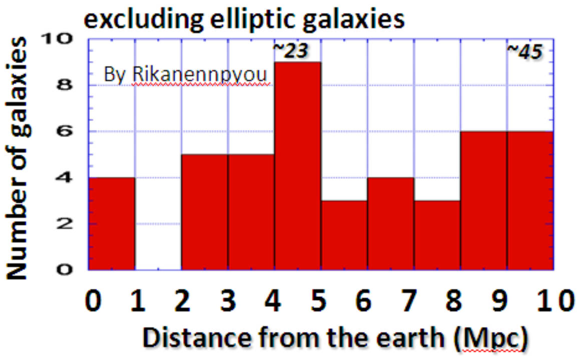

Figure 3. The number of galaxies within 10 Mpc. There are 23 galaxies within 5 Mpc and 45 within 10 Mpc. Supernovae, happened within a distance of 5 Mpc give neutrino burst for a 5 Mt detector every year.

3.3. Neutrinos from Supernovae [11]

The supernova (SN) is estimated to happen every 30 to 50 years in our Galaxy, which is based on the observed supernova rate in external galaxies, Galactic ^{26}Al abundance, historical Galactic SN rate and so on. The number of near-by galaxies can be found by flipping the reference book. There are 23 within 5Mpc and 45 within 10Mpc as shown in figure 3, excluding elliptical galaxies where we do not expect Type II SNe. By a simple count, you can expect 1 SN every 1~2 years if you are able to look for up to 5~10Mpc. Note that there are galaxies beyond 2Mpc where supernovae have more frequently happened, and therefore we can expect more SN to happen than the standard estimation. For example, there were 10 SNe during the last 90 years in NGC6946, which is 5.9Mpc from the earth and 6 during the last 60 years in M83 and so on. It is a reasonable estimate that you expect 1 SN every year within the 5 Mpc distance.

The next question is that it is possible to detect the SN neutrinos from the distance of 5Mpc. The answer is yes. There is only one neutrino burst from supernova detected on the earth in the human history. The SN1987A happened in February, 1987, at the distance of 50 kpc from the earth. The Kamiokande II detector has detected 11 neutrino events and IMB has detected 8 events. There was slight difference of the estimated core temperature by those two measurements, which gives different number of estimated neutrino events from the distance. By extrapolating the measurements we expect between 3 and 6 events in a 5 Mton detector for SNe happened at the distance of 5Mpc.

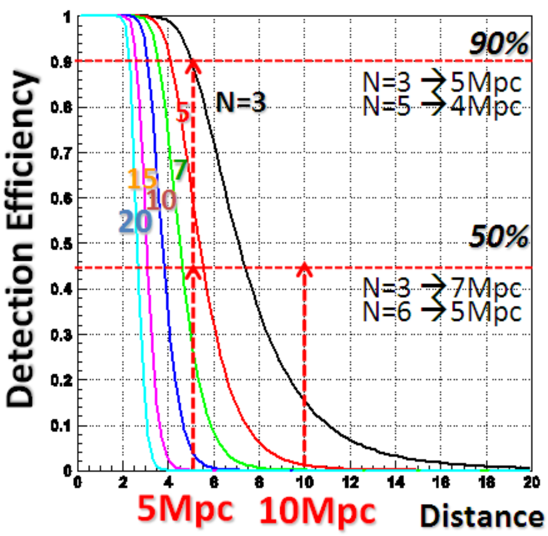

Figure 4. The trigger efficiency for the supernova neutrinos as a function of the distance from the earth. By requiring the multiplicity of 3, 90% detection efficiency is obtained up to 5 Mpc.

Most of the backgrounds come from spallation events. Usual spallation events produce more than one clustered events in space and in time. But they sometimes emit only one detectable spallation product. Accidental coincidence of such single spallation events is the serious background. However, the energy of the spallation products are below 18 MeV, therefore you can make the SN detection to be background free if you have select events with > 18 MeV. You loose about 20% of the signal, but this is not a large effect. The trigger sensitivity for the SN neutrino detection is shown in figure 4 as a function of the distance and for different multiplicity requirement of the events in 10 second. It is obvious that we are able to detect SN neutrinos almost every year. Further more we could detect 1.3 million neutrino events for a galactic supernova happening at 10kpc distance and about 2500 neutralization burst in the initial 10 ms.

3.4. How does the 5Mt detector look like [11]

There are fundamental requirements for a 5 Mt detector: 1) The detector must be scalable. It may be started with 1 Mt scale, but it can be expanded to 5 or may be 10 Mt. 2) It should be placed at least 700m deep (water equivalent) since the spallation BG may spoil for the signal detection. 3) It must be inexpensive. 4) The construction time needs to be short.

Huge 5Mt detector may be built underground, but expansion of the detector size may become difficult for the underground detectors. It may be very effective and economic if that is built under water. A detector under water is scalable, you can bring additional module for that purpose. One of those detectors may look like that shown in figure 5 [11][12]. The detector is modularized. Each module has a size of 85m x 85m x 105m, which contains 0.76 Mt of pure water. Its fiducial volume is 76m x 76m x 96 m, which corresponds to 0.554 Mt of water. And identical 9 modules make 6.79 Mt (5.0 Mt fiducial mass) detector. It is placed 1000m under water. The pure water is circulated and the water circulation system is placed on the tension leg platform (TLP) where laboratories, office building, power station, dormitory and so on will also be placed. The TLP is a commonly used technique for a station for oil wells at the North Sea for example. They have already used at places where the water depth is deeper than 1000m.

Since we use pure water, the pressure difference due to the density difference between the salt water and the pure water by 2.5% must be considered. If the pressure inside of the water tank and that of the outside are needed to be balanced at 1000 m depth, then the water head for the water tank must be 25 m above the surface of the sea. Since the platform of the TLP locates 20 m above sea level, the water head is only 5m above the platform. It matches to the height for the place of the water circulation system.

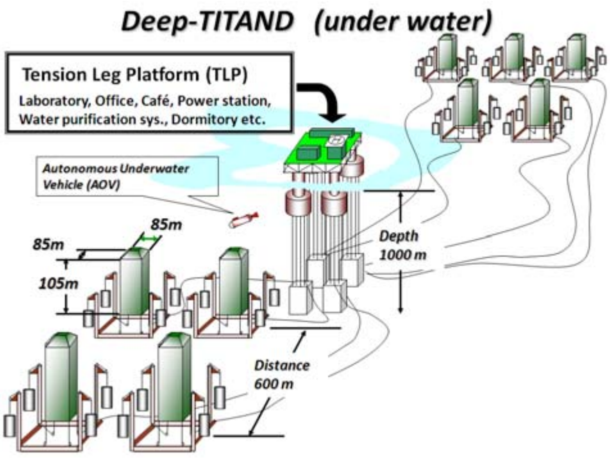

Figure 5. Schematic view of the deep under sea detector, Deep-TITAND, placed at 1000m underwater. The total fiducial mass is 5 Mton consists of 9 modules. A desalination system, a water circulation system, dormitory and so on are placed on the tension leg platform.

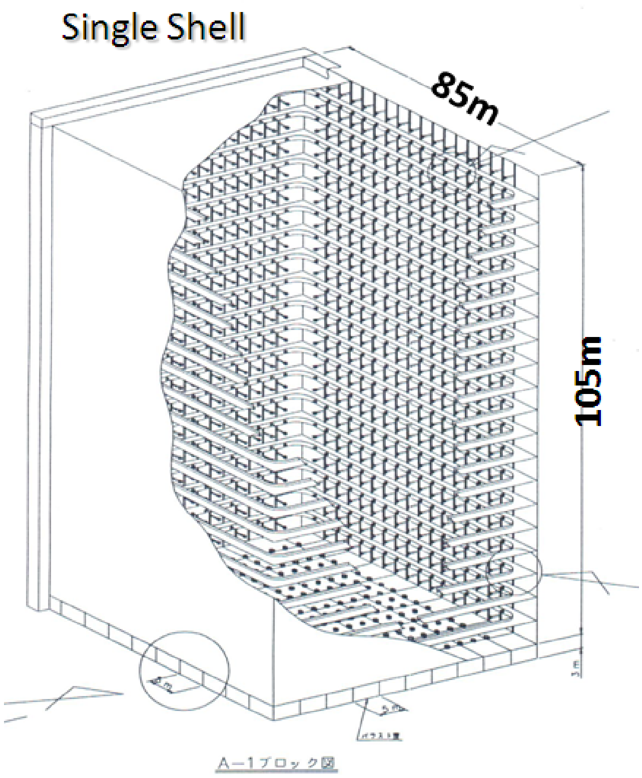

Figure 6. The internal structure of one of the unit of TAITAND. Inside of the detector wall was a structure to hold against pressure difference between inside and outside although pressure inside and outside is balanced by the water head 20 m above sea level through the 1000m distance for the pure-water inside.

The height of the water tank of 105m also creates pressure difference of 0.3 atmospheric pressure between inside and outside at top and at bottom due to the difference of the density between salt and pure water. Therefore the water tank must have a structure like semi-pressure vessel. The vessel wall has a structure to hold against the pressure difference. Light sensors must hold against the 100 atmospheric pressure. They can be kept inside of the pressure holder or they can be operated at the high pressure environment.

The detector must be placed at the site where the tidal current is less that 3 knot, in other words, less than about 1.5m /sec. Most of the places surrounding Japan are suitable except for those places where Japan Current is strongly flowing in Pacific Ocean.

The water tank and the inner structure will be made in a dock and the light sensors will also be assembled at the dock. The maximum size of the dock available in the world is 480m long and 105 m wide. This dock is located in China. Therefore the 4 units can be constructed in parallel. Those modules after completion of construction, will be tagged to offshore for loading them to the barge. We use sinking barge with the loading capacity of around 30,000 tons and move them to the installation side. We can bring a Ultra Large Crude Oil Carrier which contains pure water of 300k tons instead of oil. Equivalent to three carriers are needed to fill one unit of 760kton. The transfer speed is 10 kton per hour, roughly 30hours per ship. Once water is filled, the tank is rotated and sunk with weighs attached. A template is used to locate and fix the tank at the bottom of the sea properly.

3.5. Summary for multi-Megaton detector

In summary, a multi-megaton (typically 5Mton) detector is able to look for proton decay up to ~10^{36} yrs in addition to the standard scenario of the future neutrino experiments. We are able to detect neutrino burst almost every year from the distance of 5Mpc. The neutrino burst detections and the high sensitivity for proton decay add the value to the experiment. Precise measurement of atmospheric neutrinos is another important subject of the detector. For long baseline experiment the detector can be placed at flexible locations. The 5Mt detector has many opportunities to find unexpected phenomena. But there are many technical challenges. We need to start R&D soon for a detector to be realized more than 20 years from now.

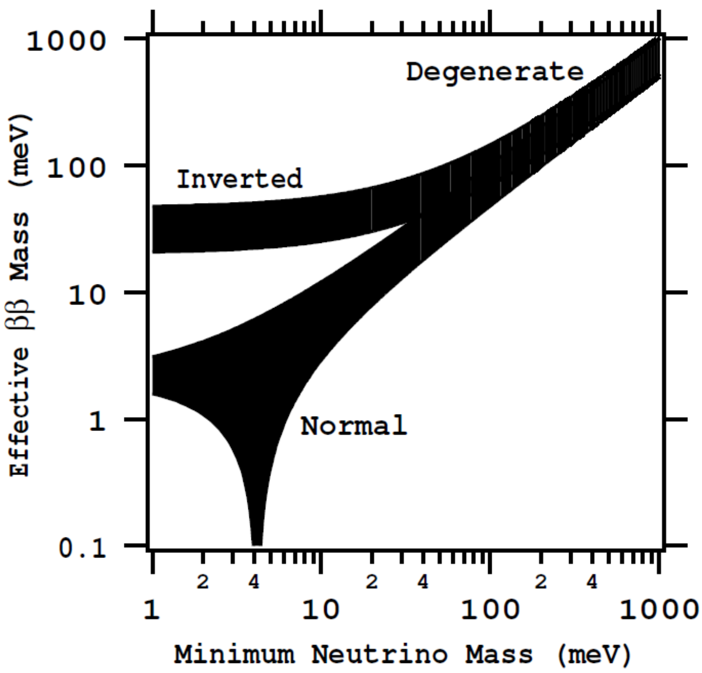

Figure 7. The predicted effective mass of neutrinos for the case of degenerate, inverted and normal hierarchy. This figure is from [13]. The recently found neutrino oscillation can make a reasonable prediction for the effective neutrino mass. The inverted mass hierarchy can be studied by the experiments sensitive to 20meV and the normal mass hierarchy can be studied if the sensitivity goes down to 2~3 meV. But there is a cancellation effect where the effective neutrino mass may not be measurable.

4. Double beta decay experiments

The double beta decay is the only experiment to judge whether neutrinos are Majorana or Dirac and is able to determine an effective mass of neutrinos. The Majorana nature of neutrinos plays crucial role, for example, for baryon number generation through a mechanism of leptogenesis. There are many experimental progresses for the last 10 years, and the lower bound for the effective mass ranges from 0.2eV to O(1eV) depending on nuclei and matrix element calculations.

From the neutrino mass difference and the mixing angles obtained from the neutrino oscillation experiments, reasonable range for the effective mass for neutrinos is predicted as shown in figure 7. The general goal of the next double beta decay experiments is to search for the mass region of 20 to 50 meV, covering the case for the inverted mass hierarchy. The experiments on going or under preparation are listed in Table 1. We hope that within a few years the experimental sensitivities will reach below 100meV.

Table 1. Double beta decay experiments planned. The most of the experiments aim to cover the region for the case of inverted mass hierarchy scenario. For more detailed discussion, see papers in these proceedings [14].

Experiments	Nucleus	Detector mass (kg)	Sensitivity (meV)	start (yr)
GERDA	^{76}Ge	15~100	780~30	2008~
SuperNEMO	^{82}Se	100	130~40	2012~
	^{150}Nd	100	70	2012~
CUORE	^{130}Te	220	120~20	2012~
EXO-200	^{136}Xe	160	550~90	2007~

4.1. Ultimate Detector

The goal of the ultimate experiment beyond the next generation experiments is clear from figure 7, which would cover substantial region predicted for the normal mass hierarchy of a few meV region. We know that most of the double beta decay experiments being conducted are not background free, and must look for a signal above the backgrounds. Therefore, in order to improve one order of magnitude of the mass sensitivity, 4 orders of magnitude improvement in experimental conditions is required. This comes from these facts that the experiments are dominated by backgrounds and that neutrino mass is proportional to square root of the life time. In order to achieve this, for example, the detector mass should be increased from a typical mass of the next generation experiments of 100kg to 10tons and the backgrounds must be reduced to 1/100. Since the typical background level of the current experiments are ~3x10^{-6}/kg/keV/day (dru), then an ultimate experiment must has a purity of ~10^{-8}/kg/keV/day (dru). The allowed internal contamination is required to be less than 10^{-16}g/g for U/Th. The question is whether this level of background of ~10^{-8} dru is possible to achieve or not. The answer is yes, because this level of background is already achieved in a water Cherenkov detector. In a fiducial volume of Super-Kamiokande, the background level in lower energy region around 5 MeV is 10^{-8} dru and most of the background comes from the energy resolution tail of ^{214}Bi decay with E_{max}=3.6 MeV. If you remove this known source of the background, the level of the background becomes 10^{-9} dru. In the high energy region around 15 MeV, the background level is 10^{-11} dru. Although there are many differences between water Cherenkov detectors and double beta decay experiments, but the background level of 10^{-8} dru talking about here is not completely unachievable.

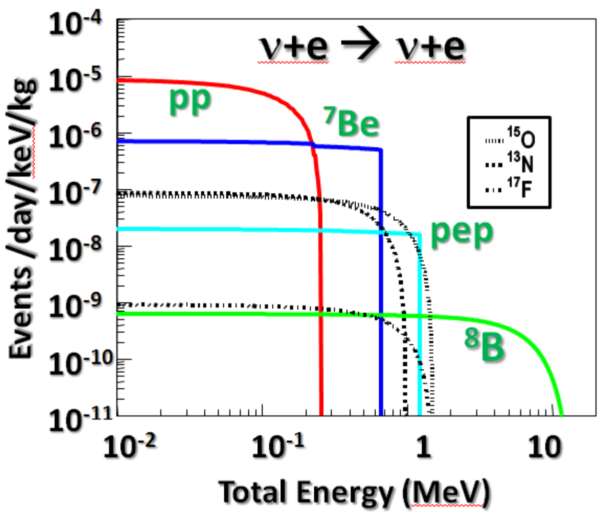

Figure 8. The energy spectrum of the solar neutrinos in unit of dru as a function of total energy of recoil electrons. The signal level of ^{8}B solar neutrinos is a few x 10^{-10} dru in a few MeV region and that of pp-neutrinos is about 10^{-5} dru in the energy range less than 100 keV

4.2. Ultimate Background

There are many sources for backgrounds: internal contamination of U/Th, external γ-rays and neutron, cosmogenics and so on. We have to fight against those backgrounds and reduce them. In addition to that, there are other kinds of backgrounds that are irreducible in some sense. These ultimate backgrounds for the double beta decay experiments in the energy region of around a few MeV are a single electron event from ^{8}B solar neutrinos through ν+e→ν+e interactions as shown in figure 8. The level of these electron backgrounds from neutrino electron elastic scattering is a few x 10^{-10} dru. The discrimination of double electron events from single electron events is necessary when the detection sensitivity gets better than this level. Also in order to enhance the signal, enrichment is MUST where the signal could be increased while keeping the background from solar neutrinos same.

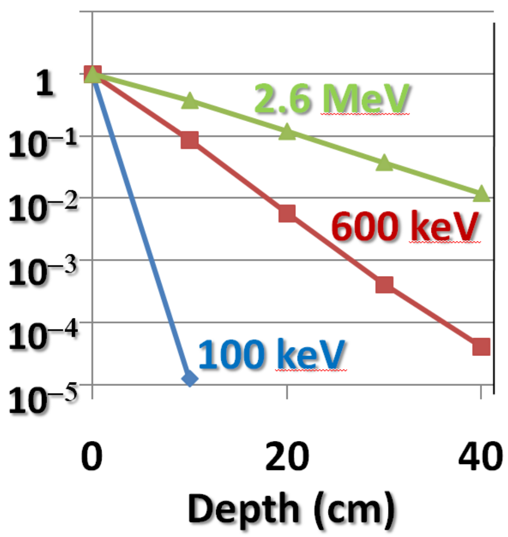

Figure 9. Self-Shielding effect for liquid Xenon as function of depth. The shielding effect is large for low energy γ-rays and more than 5 orders of magnitude reduction can be obtained in 10 cm for 100keV. But it is less effective for higher energy γ-rays. Only two orders reduction can be seen for 2.6 MeV events.

4.3. Other scientific opportunity

As we have discussed at the beginning of this paper, the ultimate experiments must have other subjects. Detectors for double beta decay may explore the dark matter search and also detect low energy solar neutrinos as a bread and butter subject though the energy region of interest is slightly different. This possibility was discussed in many occasions and partly done in the past experiments although the sensitivity was not good enough. Good double beta decay experiments also presented results on dark matter. But for the ultimate detector it is a MUST, or it is very difficult for the single purpose detector to get funded.

Low energy phenomena like dark matter and solar pp neutrino are easier than double beta decay as long as the external backgrounds is concerned since as shown in figure 9 the self-shielding is very effective. For the low energy events more than 5 orders of magnitude reduction in 10 cm of liquid xenon is obtained whereas in double beta decay region only 2 orders reduction even with 40 cm depth is possible.

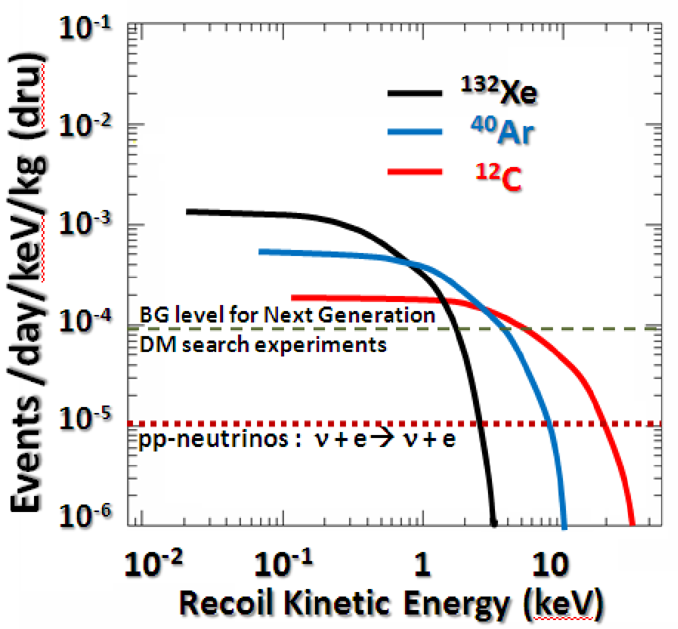

Figure 10. Energy spectrum of recoil nucleus by coherent scattering of ^{8}B solar neutrinos. Data from reference [15]. High A material like Xe has sharp, but soft energy peaks towards low energy and low A material like C has a hard spectrum. If the energy threshold can be set at a few keV, these backgrounds are not problem for high A material like Xe , but for the detectors using carbon they may be irreducible backgrounds.

The signal level for pp-solar neutrinos is 10^{-5}dru (<100keV) and therefore background level must be smaller than 10^{-5} dru. But coming DM experiments are in the region of 10^{-4} dru (aiming to detect the spin independent interaction of 10^{-45}cm^{2}) and therefore we will see solar pp-neutrinos relatively soon though large mass of about 10 tons is necessary.

One note that we have heard in this conference that the recoil nucleus from the coherent scattering of ^{8}B neutrino interaction makes forward peak and may become a potential problem of the dark matter search shown in figure 10 [15]. The coherent scattering peak is very sharp in low energy side. For Xe, it peakes <2keV (@10^{-4}dru) and for Ar it is up to <3keV. High A material may not have any problem, since in anyway they have a

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certain energy threshold above those energy. But it needs careful consideration for gas-chamber using C or F where interaction tail smears in higher energy.

The requirement for the level of background contamination in low energy is modest. For external background, self-shields work and you can use water for shielding neutrons. Internal backgrounds are allowed up to 10^{-16}g/g, which is same level for double beta decay requirements.

The mutual obstructive among the signals, of double beta decay, dark matter, pp-neutrinos, become the most problem for the ultimate detector. For dark matter search, electron signal from solar neutrino interaction is important. A single electron and nuclear recoil separation is necessary. Note that the coherent scatterings of ^{8}B neutrinos are irreducible, but the phase of the annual time variation is almost opposite. For pp-neutrinos, not only the dark matter signal, but the 2ν double beta decay signal becomes serious backgrounds though it depends on its lifetime. If this becomes important, single and double electron discrimination becomes important. If we have two different detector configurations for double beta decay and dark matter/pp-neutrinos, depletion of the double beta decay isotope is attractive for the dark matter /pp-neutrinos. However, it is better to have single ultimate detector to do everything if possible.

It is easy to say to reduce background, but it is very difficult to really reduce background. We have spent 5 years to reduce the U/Th contamination in phototube. A typical contamination of the PMT at the beginning was 180mBq and 69mBq for U and Th, respectively and in the end we obtained 1mBq for both U and Th. But further improvement is very very difficult and long way to go.

4.4. What is a choice

The Ultimate detector for the double beta decay search need to have an ability to separate signals among nuclear recoils, single electrons and double electrons. It is a difficult demand and a big challenge. Reduction of the other backgrounds must be done to that level.

You need to select material for the double beta decay nuclei and make a selection of detector technology. You probably need 10 ton of the target mass and the background level of 10^{-9} to 10^{-8} at the energy region of a few MeV and 10^{-6} dru around the energy less than 500 keV. If your detector meets these requirement, then you can request a budget for your ultimate detector for double beta decay.

5. Summary

The size of the ultimate detectors, both for Multi-Megaton and for double beta decay, beyond the next generation detectors will be huge and there will be many technical challenges. We have heavy head wind against us like the problem of the world economy, increasing the material price, sub-prim problem and so on. Also the general public want innovation, not basic science. Taking account those facts, the next to next detectors will be the only one experiment in the world, and therefore must have various other opportunities by including bread and butter subjects. It cannot be supported by a single country and must be an International Collaboration. We need to start R&D soon for that direction.

How can we establish the worldwide efforts for the only one experiment? We had better to avoid making a political framework first. We need to start R&D from bottom up by, for example, exchange of information, technology and people. Exchange of people is crucial point. Through those processes, we can start to trust each other. Then the bottom-up efforts can naturally form international working groups. Then, dream is power of progress and prepare for the future.

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