Light attenuation detection for ^{48}Ca double beta decay experiments

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Light attenuation in the development of new large scale neutrino detectors looking for the neutrinoless double beta decay is an important concern, this paper talks about the development of a detector to measure light attenuation in a medium, specifically in calcium hydroxide. The detector can also be used as a PMT tester. This paper also offer a general explanation of the physics behind the large scale neutrino detectors.

Keywords: Double beta decay, Light attenution in neutrino detectors, Cherenkov detectors, PMT testing

I. INTRODUCTION

There are unanswered questions in the field of neutrino physics such as if the neutrino is its own anti-particle or not, neutrino mass and lepton-number conservation. Double beta decays are known to be a very rare process in nature and can only happen in few isotopes. Studying these decays can give us a better understanding of the standard model of particle physics. In theory there are two types of double beta decay: two neutrino decay and if the neutrino is its own antiparticle the neutrinoless decay. If neutrinoless is demonstrated then questions described above can be answered. Building a large scale detector for the research of neutrinos involves a lot of important details, one of them is the understanding of light attenuation in the medium for the better understanding of the signal captured by the PMT's[1] . This paper will try to explain in a simple way how large scale neutrino detectors work; it will also describe the elaboration of a detector in order to measure light attenuation in water as well as a PMT's tester.

II. BACKGROUND

A. Neutrino

A neutrino is a fundamental particle predicted by the theorist Wolfgang Pauli who postulated the neutrino due to the fact that neither momentum nor energy were conserved in certain radioactive decays. Neutrinos are fundamental charge-less particles with very little mass $M_\nu < 0.44\ eV$ at 95% [5]. These particles don't interact with electromagnetic forces; instead they are only affected by the weak force. There are different types (flavors) of neutrinos associated with other elementary particles.

TABLE I. Types of neutrinos

Neutrino Flavor	Associated particle
Electron neutrino (ν_e)	Electron (e^-)
Muon neutrino (ν_μ)	Muon (μ^-)
Tau neutrino (ν_τ)	Tau (τ^-)

Neutrino mass differences were found experimentally and lead us to two different unknown scenarios due to the mass differences in the eigenstates and mixing angles. These two scenarios are called "normal hierarchy" and "inverted hierarchy" and are shown in Fig. 1. [2]

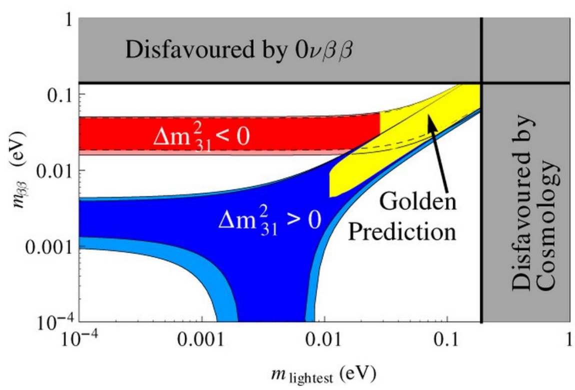

FIG. 1. Two scenarios of effective neutrino mass [2]

B. Beta Decay

A beta decay is a nuclear process where a neutron from the nucleus of an atom is transformed into a proton; the inverse process where the proton is transformed to a neutron is called inverse beta decay. At the same time with this happening an electron and an anti-neutrino escape from the nucleus. This electron and anti-neutrino

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[1] Photo-multiplier tubes are devices that can transform photons into an electric signal, their mechanism consist in the photoelectric effect and a number of dynodes which amplifies the signal. There are onging researchs dealing to do more sensitive PMT's for the measuring of light

share energy in a way in which energy and momentum are conserved, the process is shown in the next Feynman diagram.

$$n \longrightarrow p + e^{-} + \nu_e \tag{1}$$

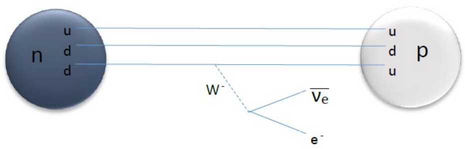

FIG. 2. Feynman diagram

C. Double Beta Decay

Double beta decays happen when a single beta decay is energetically forbidden (Fig. 3). The isotopes where this phenomenon occurs are: ^{48}Ca,^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe and ^{150}Nd

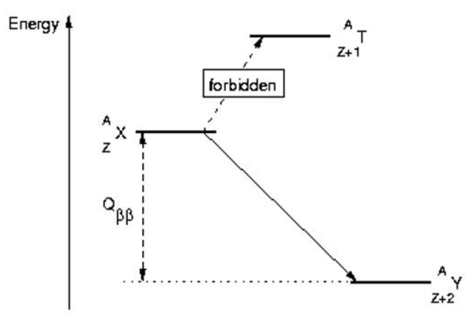

FIG. 3. Energy scheme for the double β^- decay from parent nucleus AX to daughter nucleus AY. The single β^- decay to the intermediate isotope AT is forbidden by the energy conservation rule. [15]

There exist two types of double beta decay, two neutrino $2\nu\beta\beta$ and the neutrinoless $0\nu\beta\beta$. The corresponding Feynman diagrams are below (Fig. 4)

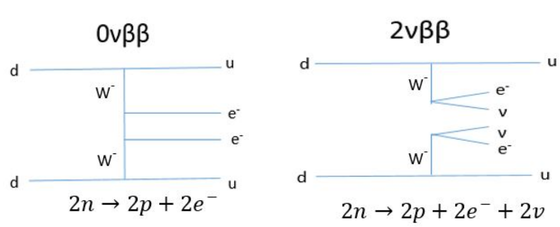

FIG. 4.

Research in the $0\nu\beta\beta$ case is important for determining if neutrinos are Majorana or Dirac particles, if neutrinos are Majoranas particles then the lepton-number is not conserved (ΔL=2) which may explain the matter anti-matter asymmetry of our universe. The rate of the neutrinoless double beta decay depends on the neutrino mass. This mass is unknown and many experiments are trying to measure it. The energy spectrum with which the betas (electrons) are ejected in the $2\nu\beta\beta$ is generally predicted by equation 2 [4]:

$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n [p_1 \varepsilon_1 F(\varepsilon_1)][p_2 \varepsilon_2 F(\varepsilon_2)] \tag{2}$$

Where:
C is independent of ε_1 and ε_2
ε_i is the energy of the electron i=1,2
$F(\varepsilon_i)$ is the Fermi function
n is the Index phase space
Q is the $Q - value$, which means the total amount of energy shared by e^- and ν_e

The energy spectrum of the $0\nu\beta\beta$ should be a Dirac Delta on the Q-value, which means that the two electrons are carrying all the energy of the decay.

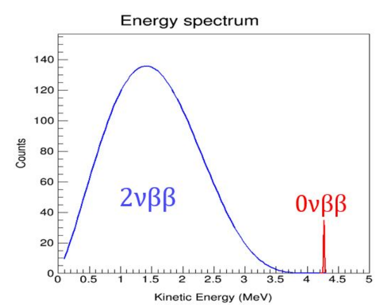

FIG. 5. $2\nu\beta\beta$ and $0\nu\beta\beta$ spectra

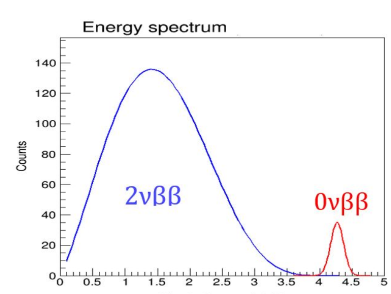

FIG. 6. Because of the uncertainty of our measurements the spectra that we are expecting should be looking like this for liquid scintillation

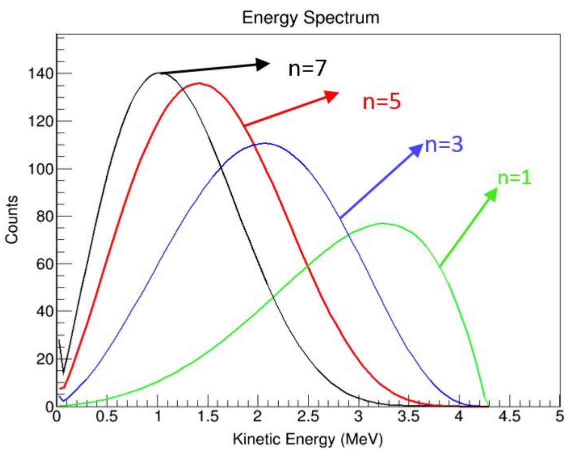

FIG. 7. Energy spectra of the different phase modes that the double beta decay can occur, $(Q-\varepsilon_1-\varepsilon_2)^n$ when $n=7,3$ or 1 the decay involves the emission of a majoron particle while the $n=5$ is the normal double beta decay [14]

D. Propetries of ^{48}Ca

^{48}Ca is the isotope with the highest Q-value (4.271 MeV) of any double beta decay mode, this makes it the best candidate for measuring the kinetic energy of their betas. Also ^{48}Ca is the only isotope that can be treated exactly in the nuclear shell mode. $2\nu\beta\beta$ half-life has been measured in many experiments, the value measured by analyzing 1555 days of NEMO3 data with $6.99g$ of ^{48}Ca was found to be $T_{1/2}^{2\nu\beta\beta}=4.11^{+0.23}_{-0.2}(stat.)\pm 0.26(syst.)\times 10^{19} years$, also one of the most accurate calculation for its nuclear matrix element was made and it marked $M_{2\nu}=0.0271\pm 0.0015$. A limit in the half-life of the $0\nu\beta\beta$ was also calculated as $T_{1/2}^{0\nu\beta\beta}>1.8\times 10^{22} years$ and this corresponds to a limit on the effective Majorana mass of $M_\nu < 19.8eV$ which corresponds to a matrix element of $M_{0\nu}=0.72$. The natural abundance of ^{48}Ca is only 0.187%. All these results come from the NEMO3 experiment. [10]

E. Detectors

Water Cherenkov detectors consist of large volumes of pure water surrounded by photomultiplier tubes (PMTs). This kind of detectors have certain features such as being able to store a lot of mass, extremely low radioactive contamination (undergrounds detectors), very sensitive and carefully calibrated PMTs to measure low signals and fast electronics transforming the pulses into a nice triggered, amplified, discriminative and digitalized pulses to be counted by a computer. Examples of these types of detectors are: Sudbury Neutrino Observatory (SNO) in Canada [8] and Super-Kamiokande in Japan [7]. Future detectors will be constructed to keep on researching neutrino science. The detectors use a phenomenon called Cherenkov radiation, which may be used for imaging high-energy particles. When the speed of the particle is greater than the speed of light in the medium ($c_{medium}=c/n$, n=refracting index), photons mostly in the ultraviolet section are emitted. This is an analogous thinking as the sonic boom effect because it generates a similar cone. The light cone that is generated on the detector is a function of the speed of the particle and its refractive index is given by:

$$\cos\theta = 1/\beta n \tag{3}$$

Another important aspect that should be pointed out is the number of photons produced by each particle. The amount of photons emitted in the detector is proportional to the speed of the electron; it is important to emphasize that the speed of the particle does not affect the wavelength of the photons (Fig 8).

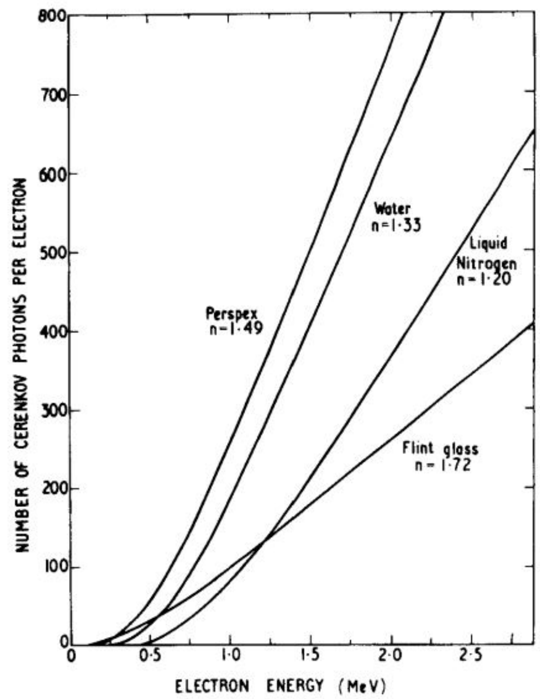

FIG. 8. Calculated yield of Cherenkov photons in the 300-600 nm wavelength region for several detection media [17]

To receive this signal, detectors are covered with PMTs that help transform the photons into an electrical signal. The threshold of Cherenkov detectors is given by: $\beta=\frac{1}{n}$ where n is the phase refracting index of the material and β is related to the kinetic energy of the electron traveling in the medium with this relation:

$$\beta = \sqrt{1-\left(\frac{1}{\frac{E(KeV)}{mc^2}+1}\right)^2} \tag{4}$$

$$E(KeV) = mc^2\left[\frac{1}{1-\beta^2}-1\right] \tag{5}$$

The water refractive index is 4/3, which gives us a minimum of 261.55 keV for the electron to generate a Cherenkov radiation [16].

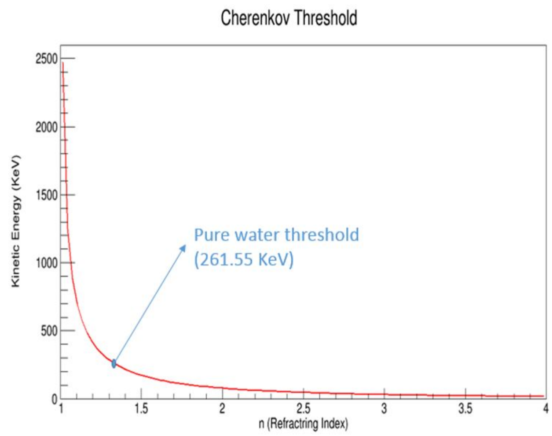

FIG. 9. Kinetic energy of the particle as a function of the refractive index of the medium

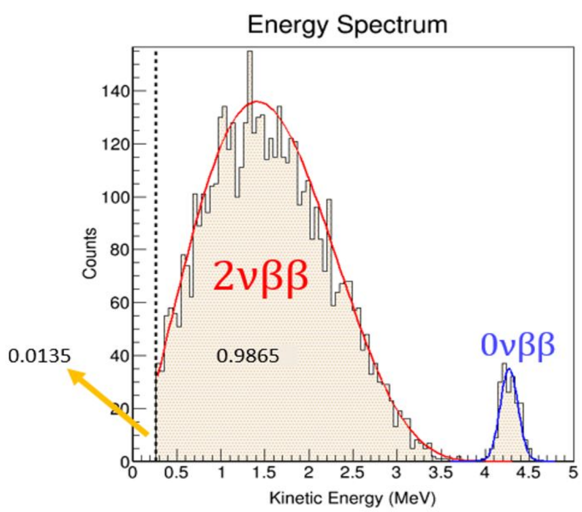

FIG. 10. Simulation of an energy spectrum of a double beta decay taken from a water Cherenkov detector

Selecting the size of the detector is a very important decision in neutrino science. For determining the dimentions, several things should be taken into account such as: the natural abundance of ^{48}Ca, $T_{1/2}^{0\nu\beta\beta}$ and light attenuation. This means that our energy spectrum will suffer another threshold due to the sensitivity of the PMTs to catch photons. Another property of Cherenkov detectors is that the time of light emitted by the particle is in the order of picoseconds due to the quick decrease of its speed this timing is important in the selection of the PMTs for the detector.

III. ATTENUATION

Attenuation generally refers to the gradual loss of a wave that is passing through a medium. In most of the cases attenuation is measured by the Beer-Lambert law.

$$I(x) = I_o e^{-\mu x} \tag{6}$$

Where $I(x)$ is the number of photons after a certain length x, I_o is the number of initial photons and μ is the Linear attenuation coefficients. Linear attenuation coefficient for photons with energies corresponding from $10^{-3}MeV$ to $10^{2}MeV$ in water have been calculated by NIST (Fig. 11); however, there are no values for photons in the ultraviolet section. Average linear attenuation coefficients for UVs with wavelengths of 253, 302 and 365 nm have been calculated by a thermoluminescence detector and registered 0.0293, 0.0205 and 0.0176 cm^{-1} respectively [13]. Our detector is aiming for data that will match with these values. After having these results, our detector will be completely calibrated for measuring another type of light attenuation in a Cherenkov detector such as the light attenuation of Ca+H_2O = $Ca(OH)_2$, calcium hydroxide. Light attenuation in calcium hydroxide will help to determinate the size of the detector with the task of not losing too much photon energy on their way to the PMT so they stay above the PMT threshold.

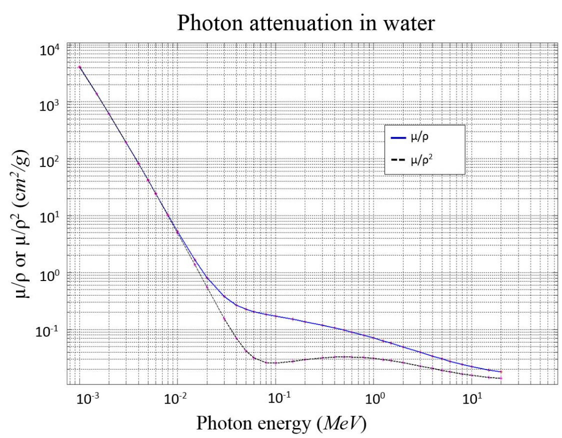

FIG. 11. NIST data for light attenuation in water[4]

IV. MEASURING LIGHT ATTENUATION AND PMT TESTING DETECTOR

The detector consists of a 2.433 metric ton dark polypropylene tank. It has a diameter of 1.32 m and a height of 1.778 m. To keep it dark it has been painted black on the outside (Fig. 13) and covered with a clean dark tarp on the inside (Fig. 14) . On the bottom part, the tank will have five calibrated waterproofed LEDs arranged on PVC tubes (Fig. 15); in the top it will have a PMT arrangement made with plastic sheets. The design is still being debated but the most recent design is shown in Fig. 16. The PMT that our detector will use is a Hamamatsu R11780 12 inch (Fig. 17) which has efficiency levels peaking up to 32% in wavelengths corresponding to 390 nm [18]

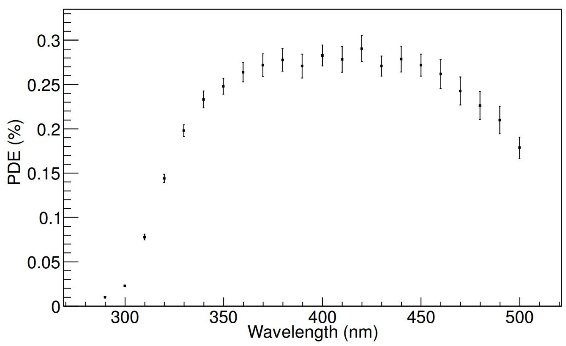

FIG. 12. The measured particle detection efficiency of the 12" R11780 PMT with standard quantum efficiency [18]

The detector will have a deionized water circulation system in order to mantain clean water around 25 °C and ∼18.18 MΩ-cm.
The detector will work in the following way: LEDs will be calibrated to produce the same amount of photons and programmed to flash in a specific moment, then the PMT will detect the photons and an electrical signal will be sent to a VME SIS3316 digitizer, which has a speed of 125/250 MS/s per channel (Fig. 18), in its final way the pulse will reach the linux system to be counted and registered. A following sketch with the whole system is shown in the next page (Fig. 19).
Measurements will be taken with water until the detector is calibrated with the NIST data (Fig. 11). When the detector is calibrated, ^{48}Ca will be added bit by bit and data for light attenuation in calcium hydroxide will be collected.
With the programmed arrangement of LEDs in different angles from the PMT center, our detector will be used to test PMT efficiencies depending on the hitting location of the photon, these measurements can be done in water as well as in calicum hydroxide.

V. CONCLUSION

Large scale experiments for research on neutrinoless double beta decay are being developed with more precise detectors and devices. Properties of ^{48}Ca have shown that it is a good candidate for these types of experiments. The light attenuation in water is an important measure for determining the size of the detector as well as the amount of calcium that is needed. This paper is a modest explanation of the physics behind these experiments as well as the development of a detector to measure light attenuation which can also be used as a PMT tester.

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FIG. 13. Painting the detector with black

FIG. 14. Cleaning the tarp

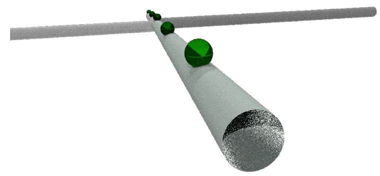

FIG. 15. LEDs arrangement

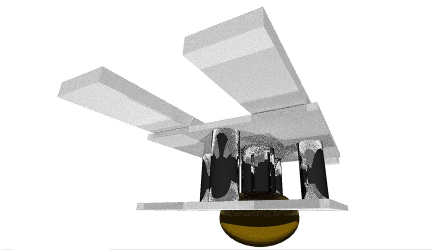

FIG. 16. PMT holder

FIG. 17. Hamamatsu R11780 12 inch

FIG. 18. VME SIS3316 digitizer

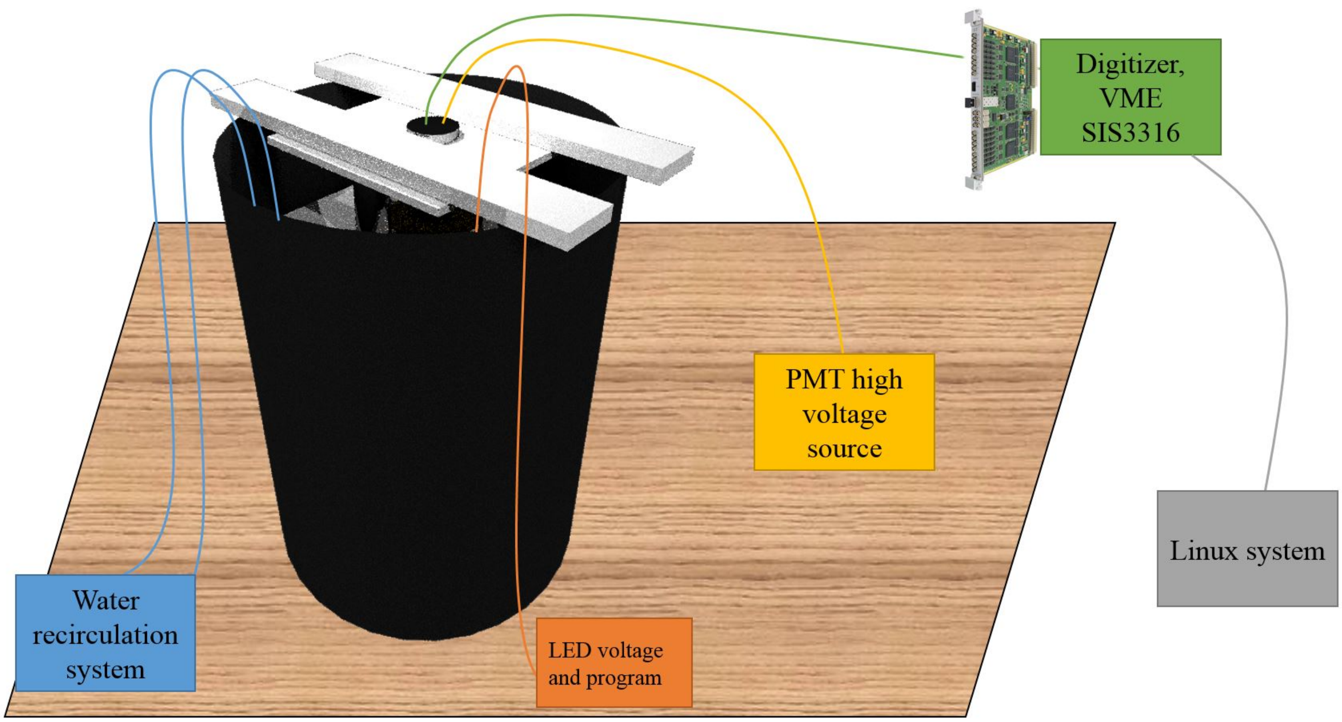

FIG. 19. Sketch of the whole detector system

VII. REFERENCES

[1] Truman S. Light, Stuart Licht, Anthony C. Bevilacqua, Kenneth R. Morash *The Fundamental Conductivity and Resistivity of Water* 2005.

[2] Stephen F King and Christoph Luhn 2013 Rep. Prog. Phys, 76 056201

[3] Klapdor-Kleingrothaus, H.V *Seventy Years of Double Beta Decay: From Nuclear Physics to Beyond-standard-model Particle Physics* 2010

[4] P. Bamerta, C.P. Burgessb and R.N. Mohapatrac *Multi-Majoron Modes for Neutrinoless Double-Beta Decay* 1995

[5] G. Hinshaw et al (2012) arXiv1212.5226

[6] André de Gouvêa and Petr Vogel *Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model* 2013

[7] http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

[8] http://www.sno.phy.queensu.ca/

[9] Petr Vogel *Neutrinoless double beta decay* 2006: Caltech, Pasadena, CA.

[10] Benjamin Richards *Double beta decay of* ^{48}Ca *with NEMO3 and calibration development for SuperNEMO* 2013: University College London.

[11] Kate Scholberg *Supernova Neutrino Detection in Water Cherenkov Detectors* 2011: Duke University, Durham, NC.

[12] NIST.

[13] Ching-Shen Su And Shyi-Ming Yeh *Uv Attenuation Coefficient in Water Determined by Thermoluminescence Detector* 1995: Duke University, Durham, NC.

[14] K Zuber *Double beta decay experiments* 2012: Institut fur Kern

[15] The NEMO Experiment *http://nemo.in2p3.fr/physics/dbd.php*

[16] Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use, Fredericia, Denmark, September 1996

[17] Glenn F. Knoll *Radiation Detection and Measurement* 1999: Third edition. Pg.713

[18] *Characterization of the Hamamatsu R11780 12 inch Photomultiplier Tube* 2013: arXiv:1210.2765 [physics.ins-det]