Spectral measurement of reactor antineutrino oscillations at Daya Bay

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Abstract: From the foundations of the theory behind neutrino oscillations, we will report on the disappearance of neutrinos in the Daya Bay Reactor Neutrino Experiment. Using the data provided by the experiment and the programming tools exposed in the paper, we will determine their energy dependence and the best fit oscillation parameters. This analysis will result in an oscillation amplitude of $sin^2 2\theta_{13} \simeq 0.085^{+0.008}_{-0.007}$ and a mass-squared difference of $\left|\Delta m^2_{13}\right| \simeq 2.38^{+0.15}_{-0.16} \times 10^{-3}\text{eV}^2$, which is consistent with previous experimental results.

I. INTRODUCTION

In 1930, W. Pauli postulated the existence of a particle that would explain the continuum electron energy spectrum obtained from beta decay. Fermi was the one to baptise it in 1933. He named it "neutrino" or "small neutron" as it goes in italian.
The theoretical prediction of the existence of the neutrino was born, but it was not until 1956 that Cowan and Reines[1] first observed one experimentally with a nuclear reactor, via inverse beta decay (IBD). Neutrinos seemed to play a fundamental role in all nuclear reactions despite having a very low interaction probability, and they were later on observed coming not only from nuclear reactors but also from the Sun and the Earth atmosphere.
With the discovery of the three generations of leptons (electrons, muons and tau particles) came the surprising fact that each of the beta (i.e. associated to an electron), muon and tau decays had incorporated a different type of neutrino. This meant that neutrinos have three different "flavours": electron neutrinos ν_e, muon neutrinos ν_μ and tau neutrinos ν_τ. Each neutrino had a "seal of origin": electron neutrinos would only be produced in electron-related reactions, whereas muon neutrinos with muon-related ones, and so.
In 1939, Bethe proposed the CNO fussion chain as a revolutionary energy producing method for the Sun, and immediately after, the now known to be dominant pp chain. These processes implied a massive production of those neutrinos postulated by Pauli and in a well determined quantity given a model of the Sun. But later experiments (first one by Davis in the late 60's) revealed that only about one third of the predicted neutrino flux was being observed. Did this mean that Bethe's theory was wrong? The theory made high-quality predictions for many parameters, but seemed to fail on the amount of neutrinos predicted. This was called the "Solar Neutrino Problem".
An elusive man named Bruno Pontecorvo, living in the USSR at the time, suggested that if neutrinos had to have mass, it meant that they would be able to "oscillate" in flavour[2]. This would solve the neutrino problem, assuming that only electron neutrinos were created at the Sun, and on their journey to Earth, they oscillated into the other forms that were undetectable at the time.
This theory suggested that at least two neutrinos were massive and mixed, unlike what the Standard Model (SM) predicted. Neutrinos in the SM are massless and have no gauge invariant renormalizable mass term. What this massive-neutrino theory is proposing is a head-on crash with the SM and suggests new physics beyond the current established theories.
The purpose of this final project (TFG) is to shed some light to this rather "strange" discrepancy and to firmly establish that neutrinos do oscillate in flavour. This work has two distinct parts: a theoretical introduction to neutrino oscillations and a numerical analysis of experimental data by means of statistical analysis tools.

II. FUNDAMENTALS OF NEUTRINO OSCILLATIONS

For this discussion, we will follow two of the main references in the field[3][4]. In the SM, neutrinos are massless fermions that neither have strong nor electromagnetic interactions. They only interact via weak interaction. In 1957 a famous experiment[5] established that neutrinos had negative helicity. As helicity = chirality if the mass is zero, when the neutrino interaction lagrangian was constructed within the SM, neutrinos were assumed to always have left chirality. The problem is that left handed neutrinos (ν_L) together with gauge invariance imply zero mass for the neutrino. This is easy to understand if we build a simple Dirac mass term like:

$$\begin{aligned} \mathcal{L}_D &= -m\bar{\nu}\nu \\ &= -m\left(\bar{\nu_L} + \bar{\nu_R}\right)\left(\nu_L + \nu_R\right) \\ &= -m\left(\bar{\nu_L}\nu_R + \bar{\nu_R}\nu_L\right), \end{aligned} \tag{1}$$

which cannot be constructed because no ν_R exists. But to fit the neutrino oscillation theory we need massive neutrinos, and thus we have to extend the SM. One way to

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do so is by hypothesising that there are certain types of particles that do not interact via SM gauge interaction, but give mass to our familiar neutrinos. We will call *active neutrinos* to those weakly charged gauge interacting (this is left-handed) neutrinos, and *sterile neutrinos* to the right-handed massive particles giving mass to the familiar neutrinos but having no interaction in the SM (but gravity).
There are several forms by which this active-sterile neutrino *interactions* can lead to neutrino masses. But in all of them, at the end, if we started with our 3 active neutrinos and 3 or more sterile neutrinos, we would end up with n massive neutrino states. Consequently, in the neutrino mass basis, the leptonic charged current interactions are given by:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \left(\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L\right) \gamma^{\mu} U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \cdots \\ \nu_n \end{pmatrix} W_{\mu}^{+} + h.c. \quad (2)$$

Where U is the mixing matrix which contains the projections of the massive neutrinos onto the flavour states:

$$\nu_{\alpha}(x) = \sum_{a=1,2,3,\ldots,n} U_{\alpha a} \nu_a(x). \quad (3)$$

Analogous to the CKM matrix for the quarks, if there are only three massive neutrinos types, it can be shown that the mixing matrix can be written as Eq.(15) (see Appendix, with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.
The parameters that are of importance for this TFG are the mixing angles (see [3] for further details). Note also that there is a possibility of a CP-violating phase δ_{CP}.
The transition probabilities between different flavours are easily derived from this matrix. We will use basic quantum mechanics (QM) procedures. We will be dealing with vacuum oscillations and we will approximate the neutrino states as plane waves:

$$\left|\nu_i(t)\right\rangle = e^{-iE_i t} \left|\nu_i(0)\right\rangle, \quad (4)$$

and in the relativistic approximation, $E_i = \sqrt{p_i^2 + m_i^2} \simeq p + \frac{m_i^2}{2E}$. Using the QM postulates, one can derive the transition probability of an α-type to a β-type neutrino (neglecting CP-violating terms):

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i<j}^{n} \mathsf{Re}[U_{\alpha i} U_{\beta i}^{*} U_{\alpha j}^{*} U_{\beta j}] \sin^2 X_{ij}, \quad (5)$$

where:

$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{eV^2} \frac{L/E}{m/MeV}. \quad (6)$$

A neutrino-oscillation experiment is characterized by the energy E of the neutrinos and the source-detector distance L. From Eq.(6) we see the importance of different neutrino masses and mixing requirement to be able to observe neutrino flavour oscillations. The overall picture is that with three light neutrinos there are three independent angles (θ_{12}, θ_{23}, θ_{13}), two independent mass-squared differences (Δm_{21}^2, Δm_{32}^2), and one CP phase δ_{CP} (note that $\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$).

III. THE DAYA BAY EXPERIMENT

A. Experimental setup

Many experimental efforts have been devoted to establish neutrino oscillations and to finding the relevant mass and mixing parameters. Data related to solar neutrino oscillation experiments have determined with great precision the mixing angle θ_{12} and mass difference Δm_{12}^2, and atmospheric neutrino results θ_{23} and $|\Delta m_{23}^2|$. From the latter we know that $\Delta m_{21}^2 \sim 10^{-5}$ eV$^2 \ll \left|\Delta m_{31}^2\right| \simeq \left|\Delta m_{32}^2\right| \sim 10^{-3}$eV^2. The last mixing angle to be determined was θ_{13}, which for years was only bounded from above, but compatible with zero. The importance of determining the short-distance oscillations characterized by θ_{13} lies on many factors. One of them is that δ_{CP} always appears as a combination of $U_{e3} = \sin\theta_{13} e^{-i\delta_{CP}}$. Thus, if it is zero, we cannot probe leptonic CP violation. Another reason is that the mass hierarchy also depends on this angle when matter effects are taken into account[8]. In order to measure this angle, the *Daya Bay Experiment* is being conducted in 大亞灣-香港 (Daya Wan - Hong Kong, China). This is a nuclear power plant complex consisting of 6 nuclear reactors and with 8 neutrino IBD detectors[7].

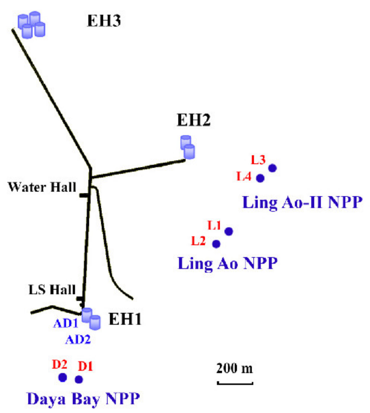

Fig. 1: Daya Bay complex. There are 6 reactors (DB NPP, LA NPP) and 8 IBD detectors at the three different halls EH1, EH2 and EH3[9].

There are two "effective" detector groups. If we look at Fig.1, there are 3 distinct halls: EH1, EH2 and EH3. Detectors at EH1 and EH2 are "near" detectors, for they are very close to their respective nuclear power plants (NPP)

(at $L \sim$ 300-500 m). The far hall is at $L \sim 1500$ m from the reactors. Antineutrinos are generated in the NPP and detected in the antineutrino detectors (AD). Each AD detects the $\bar{\nu_e}$ via IBD in a Gadolinium-doped liquid scintillator (Gd-LS). The coincidence of the prompt scintillation from the e^+ and the delayed neutron capture on Gd provides the distinctive $\bar{\nu_e}$ signature[10].
Using combined detection periods of 6-AD and 8-AD's (6 and 8 active detectors respectively) we are able work with a lot of statistics coming from the IBD candidates. The table in Fig.5 summarizes the data obtained with 8-AD.

B. Transition probability

We now focus on the disappearance factor. We will be always dealing with vacuum oscillations, neglecting effects such as the MSW effect relevant only when neutrinos propagate in large distances of dense matter[6] (for example in the Sun, or the Earth's mantle), because the distance between the NPP and the AD's is very small compared to solar or atmospheric neutrinos oscillations. Thus in the framework of three neutrino mixing the probability of detecting a $\bar{\nu_e}$ with an energy E after travelling a distance L from its source is, from Eq.(5):

$$P_{\bar{\nu_e}\to\bar{\nu_e}} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\Delta m^2_{21}\frac{L}{E}\right) - \sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{13}\frac{L}{E}\right). \quad (7)$$

In the Daya Bay experiment, the characteristic neutrino energy E is of the order of a few MeV. The L/E ratio is thus very small. In addition, $\Delta m^2_{12} \simeq 10^{-5}$ eV^2 from solar neutrino experiments, and hence the first term in the probability is very small compared to the second.

IV. MATERIALS AND METHODS. NUMERICAL TREATMENT

Once we know the basics of neutrino oscillations and the experimental setup of Daya Bay, we will use the data in table Fig.5 for the 8-AD's and the spectral data provided in [7] to determine θ_{13} and also the value of Δm^2_{13}. The analysis will consist on three sections.

A. $\chi^2(\theta_{13})$ 8-AD data analysis

First we will make a χ^2 analysis of the total event rates in each of the 8 detectors given in table Fig.5. In order to do so we will numerically generate the event rates expected from Eq.(7) with unknown θ_{13}. Several other experiments (see Ref.[10]) gave an upper bound on $\sin^2 2\theta_{13} \leq 0.1$ and a well determined $|\Delta m^2_{13}| = (2.55^{+0.21}_{-0.18}) \times 10^{-3}$ eV^2. We will use these results, together with the established ones for Δm^2_{21} and θ_{12} from solar neutrinos to generate a χ^2 test for the 8-AD data to check whether or not we can firmly assure that neutrinos do oscillate with a $\theta_{13} \neq 0$.

The corresponding χ^2 function reads [10]:

$$\chi^2 = \sum_{d=1}^{8}\frac{[M_d - T_d(1+\epsilon+\sum_{r=1}^{6}\omega_r^d\alpha_r+\epsilon_d)+\eta_d]^2}{M_d+B_d} + \sum_{r=1}^{6}\frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{8}\left(\frac{\epsilon_d^2}{\sigma_d^2}+\frac{\eta_d^2}{\sigma_B^2}\right), \quad (8)$$

where M_d are the measured IBD events of the d-th AD with backgrounds substracted, B_d is the corresponding background and T_d is the predicted number of events. The expected number of events (with oscillations) in an energy bin "i" with $E_{min,i} < E < E_{max,i}$ in a detector d can be expressed as:

$$T_{di} = \sum_{r=1}^{6}\frac{C^d}{L_{rd}^2}\int_{E_{min,i}}^{E_{max,i}} dE R_i(E)\Phi(E)\sigma(E)P_{rd}(E), \quad (9)$$

where the sum over r is over all reactors, L_{rd} is the distance of reactor r to detector d, and $R_i(E)$ is the response function for the bin i. We assume a Gaussian energy resolution, hence $R_i(E)$ can be written in terms of the error function, and we assume that it is the same for all detectors, and identical binning is used for all detectors. $\Phi(E)$ is the reactor flux (assumed to be the same for all reactors), $\sigma(E)$ is the detection cross section, P is the oscillation probability. The factor C^d contains the efficiencies and the data acquisition time (DAQ) for each detector. Those data are also given in Fig.5. To generate the theoretical fluxes, we will refer to the procedure explained in Ref.[11]. In this analysis of the total event rates we will sum over all events with neutrino energy between 0.7 to 12 MeV and call that total T_d.
ω_r^d is the fraction of IDB contribution of the r-th reactor to the d-th AD determined by baselines and reactor fluxes. The corresponding pull parameters are $\alpha_r, \epsilon_d, \eta_d$. The different σ's are the uncorrelated uncertainties of the background, the reactors (0.8%) and the detectors (0.2%).
We will write two codes in Fortan77, one to calculate the theoretical rates (dependent on θ_{13}) and another one implementing Eq.(8) and minimising it with respect to the pulls to get a best fit of the corresponding θ_{13}. In addition to the 8-AD data we will also plot the results from the AD-6 data analysis updated in 2014 found in the same reference to compare the results with improved statistics. In the 6-AD data, the "d" index in the χ^2 formula runs from 1 to 6, because only 6 detectors were working at the time.

B. Oscillation spectrum (θ_{13})

Ref.[7] also shows the observed energy spectrum of the events in the four far detectors (FD) in EH3 normalized to the spectrum observed in the four near detectors (ND) in EH1 and EH2. To analyse this data, we will generate the expected non-oscillated rates and oscillated rates to check whether the predicted spectrum fits the experimental data. In particular, we will obtain the expected number of events at the FD in each bin as

$$T_i^{pred} \equiv T_i^{FD} = \frac{\omega_{ND}}{\omega_{FD}} \frac{\sum_{d=FD} T_{di}}{\sum_{d=ND} T_{di}} (T_i^{FD})_{no\ osc.}, \qquad (10)$$

with

$$w_{ND,FD} = \sum_{d=ND,FD} \sum_{r=1}^{6} \frac{C^d}{L_{rd}^2}. \qquad (11)$$

T_{di} is obtained from Eq.(9) with the energy correspondence of each bin ı. $T_i^{FD}{}_{no\ osc.}$ is the expected unoscillated spectrum, provided also by the experiment.

C. $\chi^2(\theta_{13}, \Delta m_{13}^2)$ dependence from the spectrum

Finally, we will fit the predicted spectrum to the experimental data points with both a $\theta_{13}, \Delta m_{13}^2$ dependence. In this case, including only the statistical uncertainties for $DAQ = 372.685$ days of data taking:

$$\chi^2 = \sum_{i=1}^{bins} \frac{\left[\mathsf{DAQ}(T_i^{exp} - T_i^{pred}(\sin^2 2\theta_{13}, \Delta m_{13}^2)\right]^2}{\mathsf{DAQ} \cdot T^{exp}}. \qquad (12)$$

We will generate 50 values of the mass difference for each angle and later plot the region contours in the $\theta_{13}, \Delta m_{13}^2$ plane and acquire the best fit. The discussion of the choice of this χ^2 is explained in the conclusions.

V. RESULTS

Figures 2-4 summarize each of the numerical results and plots obtained with a brief description.

VI. CONCLUSIONS

As seen in Fig.2, we conclude that the mixing angle θ_{13} is non zero with $> 4\sigma$ confidence. And the best fit and 1σ range read:

$$\sin^2 2\theta_{13} = 0.085^{+0.008}_{-0.007}. \qquad (13)$$

The mass-squared difference fit is:

$$|\Delta m_{13}^2| = 2.38^{+0.15}_{-0.16} \times 10^{-3}\ eV^2. \qquad (14)$$

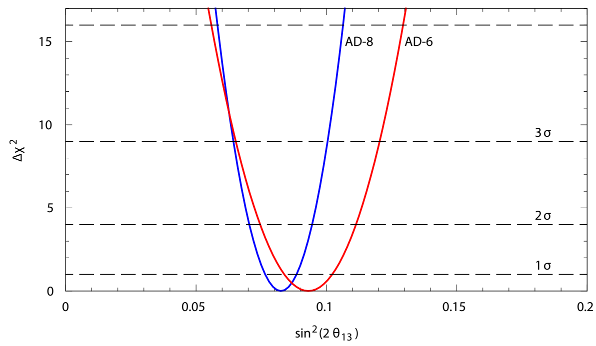

Fig. 2: $\chi^2(\theta_{13})$ fit for the AD-8 data. The minimum yields a value of $\sin^2 2\theta_{13} = 0.0825$. The y-axis has the χ^2 minimum subtracted. AD-6 data shows the importance of the number of recorded IBD events. More events mean less dispersion.

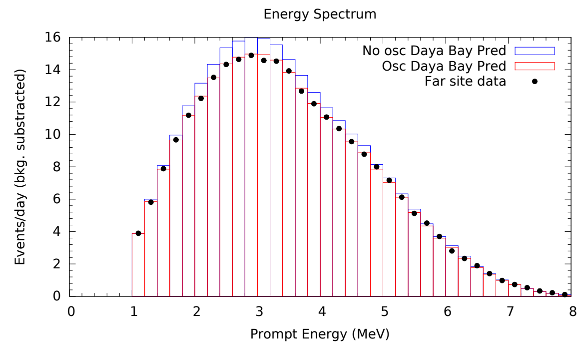

Fig. 3: The data points are the experimental energy spectrum as given in Ref.[7]. The red histogram give the theoretical prediction with the θ_{13} fit in 2. The black histogram gives the expectation in the absence of oscillation.

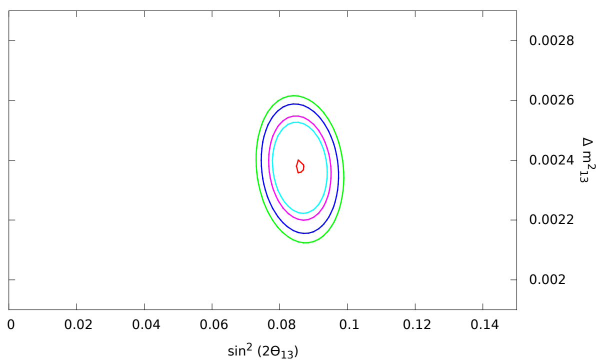

Fig. 4: Minimum and 1-4σ contours of the $\chi^2(\theta_{13}, \Delta m_{13}^2)$ function. The best fit of the minimum is: $\sin^2 2\theta_{13} = 0.085$ and $\Delta m_{13}^2 = 2.38 \times 10^{-3}$eV^2. The y-axis is in eV^2.

If we compare this results with the ones from the official Daya Bay paper [7], both are compatible. Thus our codes and procedures have led us to the "official" results. This value is consistent with previous experiments as cited previously [10]. It is also compatible with the atmospheric neutrino predictions [3].
Also, we can see the good fit of the predicted events to the experimental ones on the spectrum in Fig.3. We con-

clude that more events and thus a longer DAQ has a great impact on the results (see for example the aforementioned comparison between AD-6 and AD-8).
This non-zero result for the mixing angle may encourage new experiments to analyse the CP phase and determine whether it is zero or not as we said in section III, and also mass hierarchy in matter oscillations.
One remark must be made about the function Eq.(10). This is a simple χ^2 including only statistical error that while yielding consistent results, should be improved to tackle several other systematic uncertainty sources. Due to the complexity of the process and the length constraints in this TFG, it is left as future work.
We firmly believe that neutrinos are the key to the new insights in theoretical physics. There are many open questions, such as whether these sterile neutrinos would be part of some form of dark matter. The further we develop our experiments and the better we understand neutrinos, more light will be shed on many other topics. These neutrino experiments bring in very important results despite the lack of statistics to work with. But we have walked a very long path since Davis was trying to catch only a few a month from his mine in South Dakota, whereas now we have cathedral-sized detectors, such as Kamiokande in Japan. Neutrinos might be "ghosts" particles, but these ghosts carry a lot of new information that will be fundamental for the physics of tomorrow.

Acknowledgments

I would like to thank my advisor, Concha for putting such an effort in guiding me through this fantastic world of neutrino oscillations and for her dedication and patience over 6,000 km. To Marta and to my family.

VII. APPENDIX

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}. \tag{15}$$

8-AD Period

	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	202461	206217	193356	190046	27067	27389	27032	27419
DAQ live time(day)	374.447		378.407		372.685			
ε_μ	0.8255	0.8223	0.8574	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9746	0.9749	0.9759	0.9756	0.9762	0.976	0.9757	0.9758
Accidentals(/day)	8.62 ± 0.09	8.76 ± 0.09	6.43 ± 0.07	6.86 ± 0.07	1.07 ± 0.01	0.94 ± 0.01	0.94 ± 0.01	1.26 ± 0.01
Fast neutron(/day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
9Li/8He(/day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
AmC correlated(/day)	0.20 ± 0.09	0.21 ± 0.10	0.18 ± 0.08	0.22 ± 0.10	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.07 ± 0.02
$^{13}C(\alpha,n)^{16}O$(/day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(/day)	659.58 ± 2.12	674.36 ± 2.14	601.77 ± 1.67	590.81 ± 1.66	74.33 ± 0.48	75.40 ± 0.49	74.44 ± 0.48	75.15 ± 0.49
side-by-side ibd rate ratio	0.978 ± 0.004		1.019 ± 0.004					

Fig. 5: 8-AD data acquisition period [7].

[1] F. Reines,C. L. Cowan. "Detection of the Free Neutrino: a Confirmation". Science 124: (1956) 103-104.

[2] B. Pontecorvo. Neutrino experiments and the question of leptonic-charge conservation, Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki 53: (1968) 1717-1725.

[3] M.C. Gonzalez-Garcia, M. Maltoni. "Phenomenology with massive neutrinos". Phys. Rep. 460: (2008) 1-129.

[4] C. W. Kim and A. Pevsner, *Neutrinos in Physics and Astrophysics*, (Harwood Academic Publishers, 1993)

[5] M. Goldhaber, L. Grodzins, and A. W. Sunyar. "Helicity of Neutrinos". Phys. Rev. 109,: (1958) 1015.

[6] L. Wolfenstein. "Neutrino oscillations in matter". Phys. Rev. D 17: (1978) 2369.

[7] C. Zhang. "Recent Results From Daya Bay" (slides). Neutrino 2014, Boston, 6/3/2014

[8] Daya Bay Collaboration. " A Precision Measurement of the Neutrino Mixing Angle θ_{13} using Reactor Antineutrinos at Daya Bay". arXiv:hep-ex/0701029.

[9] Daya Bay complex. https://inspirehep.net/record/1090921?ln=en.

[10] Daya Bay Collaboration. "Observation of electron-antineutrino disappearance at Daya Bay". arXiv:1203.1669v2 [hep-ex] (2012).

[11] Th. A. Mueller et al. Improved Predictions of Reactor Antineutrino Spectra. arXiv:1101.2663v3 [hep-ex] (2011).