The possibility of leptonic CP-violation measurement with JUNO

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ABSTRACT: The existence of CP-violation in the leptonic sector is one of the most important issues for modern science. Neutrino physics is a key to the solution of this problem. JUNO (under construction) is the near future of neutrino physics. However CP-violation is not a priority for the current scientific program. We estimate the capability of $\delta_{CP}$ measurement, assuming a combination of the JUNO detector and a superconductive cyclotron as the antineutrino source. This method of measuring CP-violation is an alternative to conventional beam experiments. A significance level of $3\sigma$ can be reached for 22% of the $\delta_{CP}$ range. The accuracy of measurement lies between $8^\circ$ and $22^\circ$. It is shown that the dominant influence on the result is the uncertainty in the mixing angle $\Theta_{23}$. 

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1 Introduction

The absence of anti-matter in our Universe is a mystery for modern theoretical physics. Many different scientific hypotheses and theories were developed for a description of the solution to this issue [1]. This asymmetry may be a consequence of the Sakharov conditions being satisfied [2]. One of which is the breaking of fundamental symmetry between particles and antiparticles, so called CP-violation (CPV). In general, CPV can be represented as:

\[ P(A \rightarrow B) \neq P(\bar{A} \rightarrow \bar{B}). \] (1.1)

Equation (1.1) states that the probabilities for particles and antiparticles in symmetric processes are different. In 1964 the first evidence of CPV was observed in the quark sector in decays of neutral K-mesons [3]. Clearer confirmation of CPV was found in the decay of B-mesons [4]. Such process can be expressed in terms of CKM-mixing\(^1\) matrix. Unfortunately observed CPV in the quark sector is quite small and can not explain the current matter-antimatter asymmetry.

The leptonic sector is also a promising space within which to search for CPV. After experimental confirmation of neutrino oscillation [5], it became clear that neutrinos have mass. Furthermore, the measurement of non-zero mixing angle \(\theta_{13}\) [6] opens the door for the observation of CPV in the leptonic sector using neutrinos.

\(^1\)The Cabibbo-Kobayashi-Maskawa mixing matrix for quarks
The theory of neutrino oscillation tells us, that the phase of CPV can be observed only when one neutrino flavor converts to another neutrino flavor, wherein both flavors are known. In this paper we assume, that neutrinos are Dirac particles. The most convenient flavors of neutrino for experimental research are electron and muon neutrinos (antineutrinos). Using the standard parameterization of the PMNS mixing matrix, the transition probability between muon and electron flavors of neutrino in vacuum can be written as follows:

\[
P(\bar{\nu}_\mu \rightarrow \nu_e; \nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{21} + 
\]

\[
+ \sin 2\theta_{13} \sin 2\theta_{23} \sin \Delta_{31} \sin \Delta_{21} \cdot \cos(\Delta_{31} \pm \delta_{CP}),
\]

where \(\Delta_{ij} = \Delta m_{ij}^2 \cdot L/(4E_\nu)\); \(\Delta m_{ij}^2\) – the neutrino mass squared difference; \(L\) – the distance between source and detector; \(E_\nu\) – neutrino energy. The term responsible for CPV is included as an argument of the cosine function. As can be seen from equation (1.2), if \(\delta_{CP}\) equals 0 or \(\pi\), there is no violation of CP-symmetry.

2 A nonstandard method for measuring CPV

The traditional approach to placing limits on \(\delta_{CP}\) is based on the comparison of transition probabilities \(P(\nu_\mu \rightarrow \nu_e)\) and \(P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\) or vice versa. This method allows us to observe the breaking of CP-symmetry directly. As a general rule, CPV experiments use a powerful beam with a couple of neutrino detectors. One is a near detector, and another is a far detector. The near detector is usually relatively small, and it is used to measure neutrino flux from the source with minimal oscillation probability. The far detector should be located at the oscillation maximum for given energy of neutrino, where the splitting for different values of \(\delta_{CP}\) is higher. The most common materials for the target of the detector are water and liquid argon. The ability to reconstruct direction using these materials helps greatly in suppressing background. Liquid scintillator (LSc) can also be used in neutrino beam experiments. The main experiments investigating CPV at this moment are LBNF plus DUNE [7]; J-PARC plus HyperK [8]; NuMI plus NO\(\nu\)A [9].

In addition, there are other nonstandard methods of measuring CPV, which are based on using superconducting cyclotrons, high intensity beta-beams [10].

2.1 DAE\(\delta\)ALUS as a neutrino source

The initial proposal for an experiment to probe \(\delta_{CP}\) was made in 2010 [11, 12]. The proposed experiment consisted of three superconductive cyclotrons, which are located at 1.5 km (near), 8 km (middle), 20 km (far) with a single Water-Cherenkov (WC) detector of total mass 300 kt. However, there were other proposals. For instance, to use a LSc detector (LENA) [13]. The expected energy of the cyclotrons proton beam is 650–1500 MeV/n. The power of a single cyclotron should equal 1 MW. The proton beam will hit the graphite target and produce \(\pi^\pm\). \(\pi^-\) will be quickly captured by the surrounding matter. After that the stopped \(\pi^+\) will decay at rest to \(\mu^+\) and \(\nu_\mu\), then \(\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e\). The experiment is focused

\(^2\text{The Pontecorvo-Maki-Nakagawa-Saka neutrino mixing matrix}\)
on the transition from muon antineutrino to electron antineutrino. Only one oscillation channel is considered in comparison with beam experiments, which may use four oscillation transitions ($\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$). It should be mentioned, that such a measurement is insensitive to the mass hierarchy (MH), while the traditional method requires that we know the MH beforehand. The behavior of the oscillation curve is shown in figure 1. The influence of $\delta_{\text{CP}}$ on the oscillation curve is obvious. The first oscillation maximum is located $\approx 20$ km.

The energy spectrum of muon antineutrinos is continuous with a 52.8 MeV endpoint. The total power of neutrino sources should equal 1 MW, 2 MW, 5 MW, for near, middle and far cyclotrons respectively. The expected running time is 10 years with a duty factor of 20%. The main detection channel is inverse beta-decay (IBD). This explains the choice of

![Figure 1](image-url). The transition probability between $\bar{\nu}_\mu$ and $\bar{\nu}_e$ as a function of the distance $L$ for different values $\delta_{\text{CP}}$, for fixed neutrino energy 35 MeV.

WC detector, although LSc detector can be used for such an experiment as well. A good approximation for the IBD cross-section is [14]:

$$\sigma_{\text{IBD}} \approx p_e E_e a^{-0.07056 + 0.02018 \ln E_\nu - 0.00153 \ln^3 E_\nu} \cdot 10^{-43} \text{ cm}^2,$$

where $p_e$ – momentum of the positron, $E_e$ – energy of the positron, $E_\nu$ – antineutrino energy. The expected event rate in the energy window 20–52.8 MeV for $\delta_{\text{CP}} = \pi/2$ should equal 1600 events for 10 years of measurements. The background is negligible in this energy region, and the most of it comes from atmospheric neutrinos. Signal events exceed the background fourfold for the maximal possible event rate in a 300 kt WC detector.
3 JUNO and modified DAEδALUS

3.1 Liquid scintillator detector JUNO

The Jiangmen Underground Neutrino Observatory (JUNO) is located in Guangdong province, China [15]. The 20 kt detector consists of two nested acrylic spheres placed within a high purity water pool. The inner sphere has a radius of 17.7 m, and the outer sphere radius is 20 m. The high purity of the LSc allows to achieve a new extremely low value for the energy resolution $3%/\sqrt{E}$(MeV). The main goal of JUNO is the determination of the mass hierarchy. However, as shown in this paper, this neutrino detector can also be used to measure or place limits on CPV.

3.2 Proposal

Our proposal consists of the combination of two projects, JUNO as a detector and DAEδALUS as a neutrino source. Additionally we suggest a modification of the neutrino source configuration. Instead of using three cyclotrons in different locations, we consider only two cyclotrons. One near and another far at distances 1.5 km and 20 km respectively. The approximate scheme of the experiment is shown in figure 2.

![Figure 2. Schematic layout of the experiment with two neutrino sources (near and far) and the JUNO detector.](image)

The power of the near cyclotron is 1 MW. It is needed for flux normalization and near-physics experiments [11]. For the far cyclotron there are two options. One is a standard power cyclotron of 5 MW\(^3\), and another is increased to 10 MW. Since the middle cyclotron is not included, it is reasonable to increase the working time of each cyclotron to 33% of exposure time. This is illustrated by a pulse diagram in figure 3. In principle the duty factor can be very close to 100% for single cyclotron [16]. The target material for pion production is identical to DAEδALUS (graphite), with yield of pions 0.172 per proton. The expected running time of the proposed experiment is 10 years.

\(^3\)The original proposal by DAEδALUS group
Figure 3. The running time of each cyclotron. The yellow rectangles show the beam-off time, which will be used for background measurements.

3.3 Event rate analysis

As we consider only the IBD reaction as the main channel for detecting neutrino events, the event rate can be estimated by using equation (3.1):

$$dN = \Phi(L) \cdot T \cdot n_p \cdot \sigma(E_\nu) \cdot P(L, E_\nu) \cdot S(E_\nu)dE_\nu,$$

(3.1)

where $\Phi(L)$ is neutrino flux at the distance $L$; $T$ – exposure time; $n_p$ – number of free protons in the volume of the detector$^4$; $\sigma(E_\nu)$ – IBD cross-section (2.1); $P(L, E_\nu)$ – oscillation probability function for transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (1.2); $S(E_\nu)$ – the shape of neutrino spectrum, in our case it is the Michel spectrum of $\bar{\nu}_\mu$. Based on equation (3.1) and using the latest values of oscillation parameters from PDG [17]. The estimated event rate and the shape of the antineutrino spectrum is illustrated in figure 4. As can be seen in figure 4, the maximal event rate corresponds to a CP phase of $\pi/2$, whereas the minimal value is $-\pi/2$.

$^4$The number of free protons is larger for LSc than for water
This statistical analysis includes two parts. The first part is the sensitivity of the experiment to CPV. The second part is the accuracy with which $\delta_{\text{CP}}$ can be measured.

### 3.3.1 Experimental sensitivity to discovery of CPV

The most standard approach to the quantification of sensitivity to CPV is the minimization of a $\Delta \chi^2$ function [18, 19]. This function can be written as:

$$\Delta \chi^2_{\text{CPV}} = \min(\chi^2(\delta_{\text{test}}^\text{CP} = 0|\pi) - \chi^2(\delta_{\text{true}}^\text{CP})).$$  \hspace{1cm} (3.2)

$\chi^2(\delta_{\text{test}}^\text{CP} = 0|\pi)$ refers to two different chi-square functions. One is for a fixed value of CP phase equal to 0, another is for a fixed value $\pi$. Then we minimize $\chi^2(\delta_{\text{test}}^\text{CP} = 0|\pi)$ considering both cases and whichever gives the lowest value is plugged back into (3.2). Significance level can be defined as $\sigma = \sqrt{\Delta \chi^2_{\text{CPV}}}$. The $\Delta \chi^2$ function should have approximately Gaussian distribution with mean value $\Delta \chi^2_{\text{CPV}}$ and standard deviation $2\sqrt{\Delta \chi^2_{\text{CPV}}}$ [18]. The width of this distribution gives information about 68%, 95% and etc. bands.

### 3.3.2 The accuracy of CP phase measurement

The determination of the accuracy of measurement for particular value of $\delta_{\text{CP}}$ can be calculated by minimizing the chi-square function which in this case is the likelihood function below:

$$\chi^2_{\text{CP}} = 2 \sum_{i=1}^{N_b} \left[ \mu_i^{\text{min}}(\Omega) - n_i + n_i \cdot \ln \frac{n_i}{\mu_i^{\text{min}}(\Omega)} \right] + \sum_{j=1}^{N_p} \frac{(\eta_j - \eta_j^o)^2}{(\delta \eta_j)^2},$$  \hspace{1cm} (3.3)

where $N_b$ – total number of bins in histogram; $\Omega$ is a set of parameters including CP phase and oscillation parameters $\eta_j$; $\mu_i^{\text{min}}$ – predicted counts in $i$-th bin; $n_i$ – observed counts in $i$-th bin (usually experimental data or MC events); $N_p$ – amount of oscillation parameters; $\eta_j^o$ – best fit value of $\eta_j$ (usually from PDG); $\delta \eta_j$ – one sigma error of $\eta_j^o$. All values of oscillation parameters are presented in table 1.

### 3.3.3 Monte-Carlo simulations

The observed antineutrino spectrum was built on the basis of equation (3.1) using MC methods. In this analysis, we consider two types of uncertainties: statistical fluctuations and systematic effects related to oscillation parameters. Also the energy resolution of JUNO was added to this analysis. The main source of background is atmospheric neutral current (NC) events\(^5\). Our estimation gives 439 NC events for an exposure time of 200 kt-year with\(^5\) \footnote{Most of them are reactions on carbon}
duty factor 33%. However, this background can be significantly decreased as demonstrated in [20]. Searching for a coincident signal from the decay of a final isotope can reduce background by 40%. Using pulse shape discrimination with an acceptance level of 95%, the background can be decreased eight-fold. After these manipulations the total amount of NC events is 33. Including atmospheric charge current (CC) and fast neutron events, the total background is 45 events. Moreover the experiment uses beam-off–beam-on measurements, which may help in the background subtraction. All these reasons allow us to neglect the influence of background on the result. Following the original DAEδALUS paper [11], which showed the insensitivity of δCP measurement to systematic effects associated with flux normalization. Thus we do not account for these effects in this analysis. To estimate sensitivity to CPV, 3.5K MC simulations were calculated for each sample with particular values of δCP. Both chi-squares in the function (3.2) were minimized using the ROOT package Minuit [21, 22]. Finally, the sensitivity curve was calculated with σ-level, which was defined in the section 3.3.1. σ-level was calculated as the square root of the mean value of the Gaussian distribution for Δχ²CP.

In order to determine the accuracy of a potential δCP measurement 10K MC simulations were calculated for each sample with particular value of δCP. The chi-square function (3.3) was minimized and the value of δCP was extracted. δCP should have Gaussian distribution with mean value δtrueCP. The standard deviation of this distribution gives us 1σ error for each concrete value of CP phase.

4 Results

Experimental sensitivity to CPV for JUNO is shown on figure 5. The green band shows the 68% confidence interval, based on statistical and systematic fluctuations. A 5 MW cyclotron can cover only 10% of the δCP range with a significance level of 3σ. Whereas
a 10 MW cyclotron can reach 22% of the $\delta_{\text{CP}}$ range with a significance level of 3$\sigma$. Assuming a twofold decrease of the uncertainty in the mixing angle $\Theta_{23}$, sensitivity can be increased vastly up to 33% and 45% for 5 MW and 10 MW respectively. The asymmetry in each figure can be explained by the presence of $\cos(\delta_{\text{CP}})$ in equation (1.2).

Figure 6 depicts the behavior of the uncertainty for each concrete value of $\delta_{\text{CP}}$. Two cases are considered, with systematic effects, and without. As can be seen in figure 6, systematic and statistical effects have influence on the final result. Two peaks near $\pm 90^o$ confirm the features of the uncertainty of $\delta_{\text{CP}}$ given in [23]. Our estimation shows, that the dominant contribution to systematic uncertainty comes from the mixing angle $\Theta_{23}$.

5 Summary and discussions

From this research, it follows that not only beam experiments can be used for CPV measurements. Superconductive cyclotrons are another opportunity for investigating CPV. It was shown that significance level 3$\sigma$ can be reached and the error of $\delta_{\text{CP}}$ lies between $8^o$ and $22^o$ for the best case, assuming the uncertainties of oscillation parameters are tiny. Future neutrino experiments will decrease these uncertainties, especially the most important oscillation parameter $\Theta_{23}$ for sensitivity to CPV. At the same time, LSc is a good option for the measuring IBD events in the energy window 20–52.8 MeV. This channel is not available for liquid argon detectors. Unfortunately, the prices of superconductive cyclotrons are still high. However, large scale neutrinos experiments such as JUNO, should explore all possibilities for measuring CPV. Thus far the only proposal for measuring $\delta_{\text{CP}}$ phase utilizes atmospheric neutrinos. LSc can not be used effectively for beam experiments, therefore only cyclotrons can provide adequate measurements of CPV in JUNO.
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