Capability of detecting low energy events in JUNO central detector

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Abstract: The Jiangmen Underground Neutrino Observatory (JUNO) is an experimental project designed to determine the neutrino mass ordering and probe the fundamental properties of the neutrino oscillations. The JUNO central detector is a spherical liquid scintillator detector with a diameter of 35.4 m and equipped with two independent photomultiplier (PMT) systems, approximately 18,000 20 inch PMTs and 25,000 3 inch PMTs. A trigger threshold of 0.5 MeV can be easily achieved by using a common multiplicity trigger and can meet the requirements for measuring the neutrino mass ordering. However, it is essential to further reduce the trigger threshold for detecting solar neutrinos and supernova neutrinos. Based on the 20 inch PMT system, a sophisticated trigger scheme is proposed to achieve a low energy threshold by reducing the rate of events due to radioactivity contaminants and dark noise coincidence. With the new trigger scheme, the event rate of the central detector from different types of sources have been carefully studied by using a detailed detector simulation. It shows that the trigger threshold can be reduced to 0.2 MeV, or even 0.1 MeV, if the concentration of \textsuperscript{14}C in liquid scintillator can be well controlled.

Keywords: Large detector-systems performance; Trigger algorithms; Liquid detectors

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1 Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment which is mainly designed to determine the neutrino mass ordering and precisely measure the oscillation parameters [1]. Other physics topics include observing supernova neutrinos, studying atmospheric neutrinos, solar neutrinos and geo-neutrinos, and performing exotic searches, etc. It is located in Jiangmen city in southern China, about 53 km away from Yangjiang and Taishan nuclear power plants. The experiment is now under construction and data taking is expected to start in 2021.

The core of the JUNO detector is 20 kt of liquid scintillator (LS) contained in a 35.4 m diameter sphere and viewed by about 18,000 20 inch photomultipliers (PMTs) and 25,000 3 inch PMTs. The two PMT systems, including their readout electronics, are independent. The PMT electrical signals are firstly amplified and digitized. Those containing interesting events are then selected by a suitable trigger system in an efficient and controlled way. Afterwards the data acquisition system moves the selected data events to persistent storage for later offline data processing and analysis. In this process, a trigger system with a low energy threshold is desired and essential to precisely measure \( ^7 \text{Be} \) and \( pp \) solar neutrinos and supernova neutrinos with the JUNO central detector. Measurements of \( ^7 \text{Be} \) and \( pp \) solar neutrinos can significantly improve our knowledge on solar physics. In the central detector, the flux and energy spectra of \( ^7 \text{Be} \) and \( pp \) solar neutrinos can be measured via the elastic neutrino electron scattering, where the energy of recoil electrons are continuous and the end points of their energy spectra are \( \sim 0.75 \text{ MeV} \) and \( \sim 0.3 \text{ MeV} \) for \( ^7 \text{Be} \) and \( pp \) neutrinos respectively. Therefore, a trigger threshold of 0.2 MeV or even lower is preferable, in order to accumulate sufficient data. The same requirement holds for detection channels of elastic neutrino scattering off electrons and protons for supernova neutrinos. Especially, the scintillation light of
recoiling protons is quenched, resulting in a visible energy lower than the real one. In this paper, we propose a new trigger scheme to detect low energy events based on the 20 inch PMT system, which is studied with a full detector simulation (the 3 inch PMT system is not efficient to detect low energy events, because of its low photo-cathode coverage). Based on this new trigger scheme, the event rate of JUNO central detector is estimated, which is limiting the trigger threshold and being an important input to design electronics, trigger and data acquisition systems (DAQ). It is also one of the main parameters determining the scale of computing facility for storage and computing.

This paper is organized as follows: the layout of JUNO detector is firstly introduced, followed by a description of the trigger schemes. The performance of the trigger schemes is then presented based on the full detector simulation. In the end, the event rate from different types of sources, such as physical events, cosmic muons, radioactivity background, etc., are given for the most favorable configuration.

2 JUNO detector

The JUNO detector [2] is composed of Central Detector (CD), Water Cerenkov Detector (WCD) and Top Tracker (TT) as shown in figure 1. The CD is made of 20 kt LS contained in a 35.4 meter diameter acrylic sphere with the designed energy resolution of 3% at 1 MeV, corresponding to the energy scale of ∼1200 pe/MeV. The acrylic sphere is supported by a stainless steel truss, on which ∼18,000 20 inch PMTs and 25,000 3 inch PMTs are mounted to detect scintillation light emitted from the LS. The coverage of photo-cathode is ∼75% achieved by careful arrangement of all the PMTs. The 3 inch PMT system contributes about 3% of the total coverage and the two PMT systems are independent. 5,000 of 18,000 20 inch PMTs are dynode PMTs produced by Hamamatsu with better transit time spread and others are new type micro channel plate PMTs (MCP-PMT) manufactured by Northern Night Vision Technology (NNVT) in China. The acrylic sphere is immersed in a water pool used to shield the background of natural radioactivity from surrounding environment (e.g. the rocks). The water pool also works as a water Cerenkov detector which can identify cosmic muons by detecting their Cerenkov light via ∼2000 20 inch MCP-PMTs. The water buffer between the PMTs and the acrylic sphere can also shield the radioactivity background from the PMTs and stainless steel truss. The thickness of the buffer is about 1.4 meters. On the top of the CD, a muon tracker is installed to detect muons with better position resolution.

Figure 1. Schematic view of the JUNO detector.
The electronics and readout system handles the signals from the PMTs. The flash analog-to-digital converter (FADC) is used to digitize the signals of fired PMTs with 1 GHz sampling rate and the digitized data are transmitted to the online DAQ computing farm through data links. Here the trigger system plays the role of rejecting backgrounds and keeping signal events with a sufficient high efficiency. A common trigger strategy is to select events using the multiplicity of fired PMTs, which has been successfully used by several other reactor neutrino experiments [3–5]. In particular, Borexino experiment is using a multiplicity trigger down to 50 keV energy threshold with event rate of 30 Hz. However, for JUNO, due to its large number of PMTs and PMTs’ relatively high dark noise rate, the event rate will be high even if assuming the same radiopurity as that in Borexino experiment. The common multiplicity trigger can reach 100% trigger efficiency for inverse beta decay (IBD) events with 0.5 MeV trigger threshold, which can satisfy the requirements of the neutrino mass ordering measurement. However, for some other physics topics, like the study of solar neutrinos and supernova neutrinos, a much lower trigger threshold is preferred, which is severely limited by the coincidence of PMT dark noises and event rate of natural radioactivity. Therefore, a more sophisticated trigger scheme is proposed based on vertex fitting, which will be discussed in detail in the next section.

3 Trigger schemes of CD

The common multiplicity trigger is one of the trigger schemes that can be applied in the JUNO CD. Its typical trigger time window is 300 ns, determined by the decay time of LS [6] and variations of time of flight (TOF) from event positions to each PMT. However, due to the relatively high dark noise rates (typically 50 kHz for MCP-PMT and 20 kHz for dynode PMTs) and large quantity of PMTs, a high trigger threshold has to be set in order to eliminate the coincidence of PMT dark noises. The rate (R) of PMT dark noise coincidence can be accurately calculated using the formula (3.1):

\[ R = \frac{1}{\tau} \sum_{i=m}^{N} i C_N^i (f \tau)^i (1-f \tau)^{N-i} \]  

where, \( N \) is the number of PMTs in total and \( m \) is the number of fired PMTs in the trigger time window. If the common multiplicity trigger is used, \( m \) provides a guidance to set a proper trigger threshold; \( C_N^i \) is a combination calculator; \( f \) denotes dark rate of each PMT; \( \tau \) indicates the width of the trigger time window. For the CD, a trigger time window of 300 ns is essential to keep the high trigger efficiency for physical events, and the calculated events rate caused by dark noise coincidence versus the number of fired PMTs with 300 ns (dashed lines) and 80 ns (solid lines) trigger time window are shown in figure 2, in which the re-trigger is allowed and the dark noise rate of each PMT is assumed to be 50 kHz (blue lines) and 30 kHz (red lines) respectively. The PMT dark noise is one of the main factors affecting the lower limit of the trigger threshold. And if the trigger time window is shorter, the event rate from PMT dark noise coincidence can be significantly suppressed.

In order to reduce the impacts from PMT dark noise, a sophisticated trigger scheme is proposed. The idea is to shorten the trigger time window to reduce the probability of PMT dark noise coincidence. One effective method to achieve this goal is to reconstruct event positions, then correct the TOF for each PMT with the known information of event positions and the PMT
Figure 2. Event rate caused by dark noise coincidence versus the number of fired PMTs.

In TOF calculation, the equivalent velocity of light in LS [7] can be easily calculated by using $\frac{c}{n}$, where $c$ represents the speed of light in vacuum and $n$ denotes the refractive index of LS at the peak emission wavelength of 430 nm. Then the TOF is calculated for each PMT as a ratio of the distance between the event position and the PMT position over the equivalent velocity. To avoid implementing complex position reconstruction algorithms in Field Programmable Gate Array (FPGA), we propose a simple method to reconstruct event positions with an acceptable position resolution. In this method, the CD is divided into 179 cubic volumes. For each volume, the dimension is about $5 \times 5 \times 5$ m. To get the event position, the TOF is corrected for each PMT accordingly by using the central position of each volume and looping through all the volumes. If a volume contains the event, the narrowest first hit time distribution on fired PMTs should be gotten. Then, the center of this cubic volume is considered as the event position. And the radius position of this event can be calculated. This method has been validated by simulations. For demonstration, figure 3 shows the first hit time distribution on fired PMTs in different situations, by simulating 4 MeV $e^+$ at (15 m, 0, 0) in CD. After applying TOF correction in the volume which contain the generated position of event, a much narrower distribution is obtained (the blue line). Without TOF correction, the distribution is wider (the green line). For volumes which don’t contain the generated position of event, hit time distribution is also broader (the red line).

For the real situation, it is not necessary to perform the position reconstruction algorithm, to find out the correct volume which contains the event, because FPGA can run in parallel. For each volume, FPGA can make the trigger decision independently. Take one volume as an example, the TOF correction map for this volume is calculated and saved in the register in advance. Since the trigger system runs along with a clock system, and the clock cycle is 16 ns in JUNO, in every clock cycle, the trigger system receives a collection of digital signals of fired PMTs from front-end electronics. Then, the FPGA loads the TOF correction map of this volume and correct the hit time for each PMT. After that, a trigger decision time window of 80 ns slides along the time axis with a step of 16 ns, to check if the number of fired PMTs in the time window exceeds the pre-configured threshold. If it is true, a trigger signal will be sent out to the front-end electronics and data acquisition system, at the same time, the information of event position is also known (position of triggered volume). The above processes are performed for all volumes in parallel by FPGA. We also studied other trigger time windows (48 ns, 64 ns) and found the similar performance.

With this sophisticated trigger scheme, a fiducial volume cut can be easily applied and it is very effective to reduce event rate of radioactivity, because most of radioactivity are from the outer...
region of the CD. The reconstructed positions determined by this trigger scheme are also validated by comparing with the truth positions from Monte Carlo (MC) simulation. The bias between the reconstructed and the truth positions is shown in figure 4, by using $^{14}$C events uniformly distributed in LS with energy larger than 0.1 MeV. The resolution of reconstructed positions is about 1.5 meters, corresponding to the TOF correction precision of 7.5 ns, which is much shorter than the trigger decision time window of 80 ns and agrees well with the expected value of 1.45 meters. Only $\sim 0.06\%$ of events are reconstructed with biases larger than the volume size of 5 meters, which indicates that the volumes that contain the events can be almost 100% identified.

![Figure 3](image)

**Figure 3.** First hit time of fired PMTs with different situations.

![Figure 4](image)

**Figure 4.** Differences of true vertices and reconstructed vertices for $^{14}$C events.

The performance of the new trigger scheme is carefully studied by using a detailed CD simulation software, which has been designed and implemented based on GEANT4 [8] and SNiPER framework [9]. Both the common multiplicity trigger scheme and the sophisticated trigger scheme have been implemented in the simulation software, and they are optional for users. By simulating gamma particles, uniformly distributed in CD, with three different energies (0.1 MeV, 0.2 MeV and 0.3 MeV) to mimic the physical signals, the numbers of fired PMTs with two different trigger schemes are shown in figure 5a and figure 5b respectively, in which the contribution from PMT dark noises is included. In addition, the event rate of dark noise coincidence is also shown in the plots represented by dark dotted lines. For both cases, 50 kHz dark noise rate is assigned for each PMT. Comparing the two plots, one can easily find that the sophisticated trigger scheme shows much
better performance. With the sophisticated trigger scheme, the effect from PMT dark noise can be eliminated even for 0.1 MeV physical events, while this is not the case for the common multiplicity trigger scheme.

(\textbf{Figure 5}. Maximum number of fired PMTs in the sophisticated trigger with time window of 80 ns (a) and in the common multiplicity trigger with time window of 300 ns (b) for gamma particles with different energies and event rate of coincidence of dark noise.)

In JUNO, the lower trigger threshold is preferred, but it is limited by the event rate during the data taking. As known, the event rate from radioactivity will increase when the trigger threshold decreases. So it is important to study the event rate from different sources and check how it is impacted by the trigger threshold. This work is done based on the full detector simulation with the two different trigger schemes.

4 Event rate for physical events

The events detected by the CD can be classified into physical events and background events. Physical events include all events of interest, like reactor neutrino, solar neutrino, geo-neutrino, atmospheric neutrino, etc. For each kind of physical events, the original event rate has been well estimated in the JUNO yellow book [10]. Event rates of different event types without trigger selection are summarized in table 1. The solar neutrinos account for the major part of the physical events, which can reach 0.45 Hz if no trigger threshold is applied, mainly contributed from \textit{pp} channel, where the energy of \textit{pp} neutrino is quite low.

The total event rate from the physical channels is less than 1 Hz, which is negligible compared with those from radioactivity backgrounds. However, if a supernova bursts at a typical distance of 10 kpc, neutrino event rate is estimated to be hundreds of Herz from different channels, and the event rate will be much higher in the first second during the explosion of about 10 seconds. For a supernova with shorter distance, the higher event rate is expected. The trigger scheme for supernova neutrino is under development in JUNO.

5 Event rates for background events

5.1 Cosmic muons

The JUNO detector is located underground with about 700 m overburden. Taking into account of the detailed mountain map at the JUNO site, the cosmic ray flux can be simulated by MUSIC [11].
Table 1. Event rates of different sources.

| Event source              | Rate      |
|---------------------------|-----------|
| IBD event                 | 83 per day|
| Li9/He8 β-n decay         | 84 per day|
| fast neutron              | 0.1 per day|
| C13(α, n)O16              | 0.05 per day|
| Geo-neutrino              | 1.5 per day|
| cosmic muon               | 3 Hz      |
| Natural Radioactivity     | ~1 MHz    |
| Solar neutrino            | 0.45 Hz   |
| Atmospheric neutrino      | 0.94 per day|

The muon flux in the experimental hall is estimated to be 0.003 Hz/m², and the average energy of the muons is determined to be about 215 GeV. Based on the muon flux and the size of the CD, the total muon event rate in the CD is calculated to be about 3 Hz.

The cosmic muons which go into the CD can be further classified into shower muons and non-shower muons. The non-shower muons are minimal ionization particles. The shower muons may generate neutrons and radioactivity isotopes with long lifetime, which can form delayed signals and be tagged as separated events other than the original shower muons. A detailed muon simulation shows that about 20% of muons are shower muons and the event rate induced by muons is about 5 Hz totally.

5.2 Radioactivity background

One of the main contributions to the event rate is the natural radioactivity background, which comes from various sources, such as $^{238}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$. They come from different materials in the JUNO detector. In order to control the event rate of the radioactivity background, the purity of each material used to build up the detector has to be screened and the requirements on radio-purity are driven by the sensitivity of the neutrino mass ordering. In Daya Bay experiment, the $^{235}$U/$^{232}$Th concentrations in LS are $2 \times 10^{-14}$ g/g and $4 \times 10^{-14}$ g/g respectively. While in Borexino experiment, the radioactive contamination of $^{235}$U/$^{232}$Th are lower than $9.4 \times 10^{-20}$ g/g and $5.7 \times 10^{-19}$ g/g [12]. In JUNO, a better purification system will be applied, compared with Daya Bay experiment, which can reduce the $^{235}$U/$^{232}$Th by two orders of magnitude, to the level of $10^{-16}$ g/g. For $^{40}$K, it can reach $10^{-17}$ g/g. Besides $^{235}$U/$^{232}$Th/$^{40}$K, cosmic muons continuously produce $^{14}$C from $^{14}$N, via the reaction of $^{14}$N(n, p)$^{14}$C. If the petroleum used to make LS is located deep underground and is shielded from high cosmic ray flux, one can expect very low $^{14}$C contamination in LS. But for the worst case, petroleum may locate on the surface of earth which suffers very high flux of cosmic muons, $^{14}$C abundance becomes higher. In this work, we set $^{14}$C abundance to be $10^{-18}$ g/g, which is lower than the lowest value ever measured by a factor of 2 [13]. However, the event rate induced by $^{14}$C can be easily scaled for other concentrations. The radioactivity in PMT glass depends on which kind of glasses are used to make the PMTs. In JUNO, $^{235}$U/$^{232}$Th/$^{40}$K concentrations in MCP-PMT glass are 2.5 Bq/kg, 0.5 Bq/kg and 0.5 Bq/kg respectively, for Hamamatsu PMTs, the radio-purity is several times worse than that of MCP-PMTs [14]. However, due to 1.4 meter water buffer between PMTs and LS, the event rate from
PMT glass can be reduced significantly. This effect has also been included in our simulation. The acrylic sphere is quite close to LS in which the radioactivity can easily deposit their energies in LS and be triggered to form events. Radioactivity from the stainless truss also contributes total event rate in the CD. Similar as that from the PMT glass, it can also be heavily suppressed by water buffer. The upper limits of U/Th/K concentrations in stainless steel truss are used in our simulations, which are 12.4 mBq/kg, 20 mBq/kg and 54.2 mBq/kg respectively based on reference [15]. $^{60}$Co can also be generated when cosmic muons go through stainless truss. Radon in water is required to be less than 0.2 Bq/m$^3$ in JUNO, in this way, there is negligible impact on the mass hierarchy sensitivity. And U/Th/K concentrations in rock are 10 ppm, 30 ppm and 5 ppm respectively. The requirements of upper limits of radioactive impurities in different detector materials are summarized in table 2.

|        | $^{238}$U | $^{232}$Th | $^{40}$K | $^{210}$Pb | $^{85}$Kr | $^{39}$Ar | $^{60}$Co | $^{14}$C |
|--------|-----------|------------|----------|----------------|---------|----------|----------|----------|
| LS     | $10^{-6}$ ppb | $10^{-6}$ ppb | $10^{-7}$ ppb | $1.4 \times 10^{-13}$ ppb | 50 µBq/m$^3$ | 50 µBq/m$^3$ | ~ | $1 \times 10^{-18}$ g/g |
| Glass  | 257 ppb   | 200 ppb    | 13.8 ppb  | ~              | ~       | ~        | ~        | ~        |
| Acrylic| 4.9 ppt    | 81 ppt     | 3 ppt     | ~              | ~       | ~        | ~        | ~        |
| Steel  | 12.4 mBq/kg| 20 mBq/kg  | 54.2 mBq/kg| ~              | ~       | ~        | ~        | 2 mBq/kg |

5.3 Results of radioactivity background simulation

For each material in JUNO detector, the radioactivity listed in table 2 are used as inputs in detector simulation to study its event rate. The results with different trigger thresholds are shown in figure 6a and figure 6b, corresponding to results of the sophisticated trigger scheme and the common multiplicity trigger scheme respectively. The trigger efficiencies of physical events are presented by the solid lines, determined by simulating gamma particles with three different energies and uniformly distributed in the CD. The dark noise of PMTs has been taken into account in the simulation and assumed to be 50 kHz for each PMT.

![Figure 6](image_url)

**Figure 6.** Events rate contributed by different materials in CD and trigger efficiency of physical events with different energies. (a) is from the sophisticated trigger scheme and (b) for common multiplicity trigger scheme.

The event rate increases when the trigger threshold decreases. Assuming the DAQ can accept 1 kHz event rate during the data taking, then based on figure 6, the trigger threshold can be set...
at 150 and 380 for the sophisticated trigger scheme and the common multiplicity trigger scheme respectively. In this case, the sophisticated trigger scheme can keep 100% trigger efficiency even for 0.1 MeV physical events, but the efficiency of the common multiplicity trigger scheme is only 60% for 0.1 MeV events. The trigger threshold is limited by the radio-purity of LS, in particular at low energy region and $^{14}\text{C}$ is a main contributor. $^{14}\text{C}$ goes through radioactive beta decay by emitting an electron and an electron anti-neutrino. The emitted electrons have a maximum energy of 0.156 MeV and only a small fraction (< 0.2%) of $^{14}\text{C}$ can be triggered with 0.2 MeV threshold due to energy smearing and pileup. However, more $^{14}\text{C}$ will be triggered with 0.1 MeV threshold. At high energy region (> 0.25 MeV), the acrylic and radon are the two major sources of events.

Since most of the radioactivity backgrounds come from the outer region of the CD, and the sophisticated trigger scheme has the ability to select the events in different fiducial volumes, the event rate coming from radioactivity backgrounds can be further reduced. The event rate from different radioactivity sources are summed up and the results are listed in table 3 with different trigger threshold and in different fiducial volumes. The trigger threshold is defined as the number of fired PMTs and the fiducial volumes are selected by applying different radius cuts. Based on energy scale in CD ($\sim 1200$ p.e./MeV), the threshold can be converted to visible energy with subtraction of the PMT dark noise coincidence. In table 3, the energy threshold of 200 corresponds to about 0.1 MeV visible energy where 50 kHz dark noise rate for each PMT is assumed. The events rate decreases when the fiducial volume becomes smaller, since part of radioactivity comes from the outer region of the CD, on the other hand, both the radioactivity in LS and the event rate of physical events are reduced due to the smaller target mass. This is a trade-off between the trigger threshold and the statistics of the signals.

Table 3. The sum radioactivity single rate in central detector with different trigger threshold and fiducial volumes.

| Singles Rate (Hz) | Thres.>100 | Thres.>200 | Thres.>300 | Thres.>400 | Thres.>500 | Thres.>600 |
|------------------|------------|------------|------------|------------|------------|------------|
| R<10m            | 1292       | 126        | 15         | 11         | 9          | 6          |
| R<11m            | 1338       | 134        | 19         | 14         | 11         | 8          |
| R<12m            | 1483       | 167        | 35         | 26         | 21         | 15         |
| R<13m            | 1614       | 200        | 54         | 40         | 31         | 23         |
| R<14m            | 1614       | 200        | 54         | 40         | 31         | 23         |
| R<15m            | 1703       | 228        | 71         | 53         | 42         | 31         |
| R<16m            | 2104       | 361        | 152        | 116        | 90         | 66         |
| R<17m            | 2320       | 439        | 202        | 154        | 120        | 88         |

6 Conclusion

Collecting low energy events is essential for JUNO to study the solar neutrinos and supernova neutrinos. With the proposed sophisticated trigger scheme, the effect of dark noise coincidence is significantly suppressed. The trigger energy threshold can be reduced to 0.2 MeV. If the concentration of $^{14}\text{C}$ in LS can be well controlled, such as less than $10^{-18}$ g/g, the trigger threshold can even be reduced to 0.1 MeV. The total event rate from physical events except the supernova events in JUNO is less than 1 Hz, which is negligible comparing with those from radioactivity backgrounds.
The proposed trigger scheme is also capable to trigger events in a certain fiducial volume, which can further suppress the radioactivity events coming from the outer region of the CD. The results of the present study provide important event rate estimation and trigger scheme both for JUNO design and disk storage preparation.

Acknowledgments

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