The event rate estimation for JUNO experiment *

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Abstract: ToDo

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1 Introduction

JUNO[1](The Jiangmen Underground Neutrino Observatory) is a multipurpose neutrino experiment. It is designed to determine neutrino mass hierarchy and precisely measure oscillation parameters by detecting reactor neutrinos from the Yangjiang and Taishan Nuclear Power Plants. It also intended to observe supernova neutrinos, study the atmospheric, solar neutrinos and geo-neutrinos, and perform exotic searches.

The JUNO experiment hall is located in Kaiping, jiangmen, in Southern China. It's about 53 km away from Yangjiang and Taishan Nuclear Power Plants, both of which are under construction. The planned total thermal power of these reactors is 36 GW. In addition, there are no other nuclear power plants within 200 km. The 20-thousand-ton liquid scintillator detector of unprecedented 3% energy resolution (at 1 MeV) is installed at 700-meter deep underground to suppress backgrounds.

The experiment hall is expected to be finished at 2019. It is possible to get data from the experiment at 2020. The JUNO event rate is very important for JUNO experiment design. So we want to estimate JUNO event rate by theory and Geant4 simulation. The JUNO event rate is composed of signal rate and background rate.With the estimated JUNO event rate,we can estimate the offline computing resource such as cpu, disk, which we needed to do offline data saving and analyzing.The estimated JUNO event rate can also help the online electronic design.

In the beginning, for the central detector we proposed three design options: acrylic option, balloon option and module option. According to the Geant4 detector simulation, the module option was abandoned. Since the acrylic option and balloon option are similar, we study the acrylic option to estimate JUNO event rate.

2 JUNO detector scheme

The JUNO detector is composed of a central detector, a water cherenkov detector and a muon tracker(shown in Fig.1).The central detector is a LS detector of 20kton fiducial mass and $3\%/\sqrt{E(MeV)}$ energy resolution.The central detector is submerged in a water pool to be shielded from natural radioactivities from the surrounding rock and air.The water pool is equipped with PMTs to detect the cherenkov light from muons. On top of the water pool, there is a another muon detector to accurately measure the muon track.

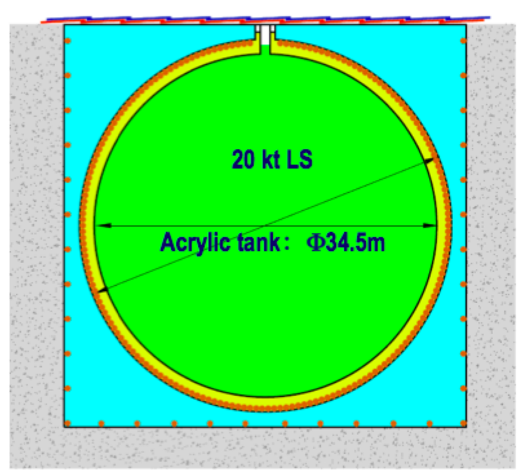

Fig. 1: Acrylic option

For the central detector, there are two design options at present. The default option is acrylic vessel with stain-

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less steel truss. The backup option is liquid balloon with stainless steel vessel. Since the two options are similar , we just consider the acrylic option when estimate the event rate.

In this option, the inner acrylic tank is spherically shaped holding 20 kton LS.The acrylic sphere is supported by the steel truss while the truss is held by some supporting legs at the bottom of the water pool in the experiment hall. The thickness of the acrylic tank is 12 cm. Between the acrylic sphere and the truss, there are many PMTs carried inward facing to the truss to detect the optical signal from LS. Ultrapure water is filled in as shielding liquid outside of the acrylics tank.

3 The source of event

The event rate we discussed is singles rate that signals from particles depositing visible energy greater than trigger system's energy threshold in LS.

Although JUNO is a multi-purpose neutrino experiment.The main physics goal is to determine neutrino mass hierarchy and precisely measure oscillation parameters by detecting reactor neutrinos from the Yangjiang and Taishan Nuclear Power Plants. So we consider the reactor neutrinos as the main source of signal event.

The reactor electron antineutrino interacts with proton via the inverse β-decay(IBD) reaction in the liquid scintillator, and releases a positron and a neutron. The positron depositsits energy quickly, providing a prompt signal. The energy of positron carries most of the kinetic energy of the neutrino. The neutron is captured by proton after an average time of 200μs, then releases a 2.2 MeV gamma, providing a delayed signal. The coincidence of prompt-delayed signals provides a distinctive antineutrino signature. The estimated IBD reaction rate is about 40/day[2].

The signals is a small part of event source. The most of the event source is background.The background is composed of the radioactivity in detector materials and detector surrounding, the cosmic muon and the electronic dark noise.

The background induced by cosmic ray muon is the main background and not easy to remove. Muon can induce high energy neutron as fast neutron background. And muon spallation can induce Li9/He8 background.

The electronic dark noise is mainly caused by thermal emission of electrons and radioactivity from components of the PMTs. Although the energy of dark noise is small, it may exceed the energy threshold when the energy threshold is low.

4 The event rate estimation of central detector

The JUNO detector consists of a central detector, a water cherenkov detector and a muon tracker.So we estimate the event rate of each part respectively.The central detector is the main part of JUNO detector.As we mentioned previously, the signal rate is about 40/day. We will discuss the background in the following.

4.1 Natural radioactivity estimation

Natural radioactivity exists in the materials of central detector. The materials of central detector in the acrylic option mainly include LS, acrylic, oxygen-free copper, stainless steel, as well as the glass of PMT. The formations of these materials in different conditions cause more or less existence of radioelement. The Rn in the water pool also induced radioactivity. The singles rate of each material's natural radioactivity in different energy threshold is listed in table.1. The detailed discussion can be found in the reference[3].

Table 1: The inner singles rates

Singles Rate(Hz)	LS	Glass	Acrylic	Steel	Copper	Rn	Sum
E>0.7MeV	2.39	2.43	69.23	0.89	0.82	17.31	93.07
E>0.6MeV	4.26	2.66	75.26	0.95	0.94	19.79	103.86
E>0.5MeV	12.06	2.83	81.49	0.98	1.06	23.36	121.78
E>0.4MeV	13.86	3.24	87.84	1.22	1.29	26.11	133.56
E>0.3MeV	15.51	3.72	98.57	1.57	1.51	31.60	152.48
E>0.2MeV	17.16	4.12	117.33	1.80	1.89	39.85	182.15
E>0.1MeV	352.36	5.27	149.26	2.22	2.60	54.97	566.68

4.2 Muon estimation

In order to reduce muon background, the central detector is located in 460 meters underground level. There are about 700 meters rock on the top of the experiment hall.Muno rate is about 0.003Hz/m^2 and average muon energy is 214GeV from simulation study[**?**]. Compared to the ground surface, the muon flux is reduced about 60000times.

The radius of LS sphere is 17.7m, so the muon rate in central detector is about: $\pi \times 17.7^2 \times 0.003 = 2.95$Hz.

Cosmic muon rays can also produce a large number of neutrons in the rock around central,these neutron can produce fast neutron background in the central detector. If water shield thickness is 2.5 meters in JUNO, fast neutron ratio is 0.3%, considering detector volume and geometry effects.

Spallation muon interact with scintillator can induce Li9/He8 background. We use the formula to estimate Li9/He8 background: $Y_n = C \times Q_c \times E^{\alpha}$.

In this formula we assume the yield is power law function of muon energy. Q_c is carbon density factor for different liquid scintillator.

In JUNO experiment the mean muon energy is 215GeV, the mass of liquid scintillator is 20kton, the muon flux is 0.003Hz/m^2, the α in formula is 1.06±0.2 .The yield of Li9/He8 is $(2.3 \pm 0.5 \times 10^{-7})(\mu g/cm^2)^{-1}$. So the Li9/He8 event rate in JUNO is 57 ± 14/day.

4.3 Dark noise estimation

To estimate the event rate of dark noise, we suppose a detector has N PMTs, each PMT has dark current rate f Hz, multiplicity trigger threshold is m PMTs, trigger integration time is τ ns. So the noise rate can be calculated by the below formula:

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

In JUNO experiment, we assume the total PMT number is 17746, the dark current rate of each PMT is 50kHz, the trigger integration time is 300ns. The number of photons which are received by PMTs is 1200, when the visible energy is 1MeV. So the estimated dark noise event rate can be shown in Fig2.

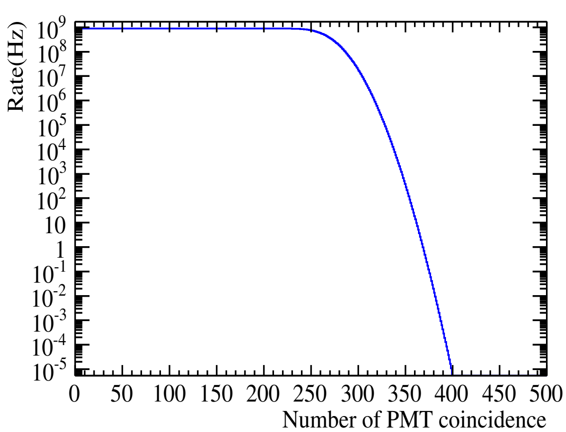

Fig. 2: Dark noise event rate when trigger integration time is 300ns

From Fig2 we can see the energy threshold must greater than 0.3MeV. So that the dark noise will induce few background event rate.

4.4 A promising secondary trigger system design

If we just study the IBD event, we can set the first trigger system's energy threshold to 0.7MeV. So the dark noise will induce few event rate, and from Table.1 we can see the total radioactivity background event rate in central detector is 75.75Hz ,when energy threshold greater than 0.7 MeV.

But if we want study solar neutrinos, supernova neutrinos and other low energy neutrino sources, , low energy threshold is very important. When the energy threshold is decreased, the background rate of radioactivity and dark noise will be increased. So we proposed a new secondary trigger system design to reduce the background rate.

We can reduce radioactivity background by the vertex of event, because the radioactivity from acrylic tank, oxygen-free copper and stainless steel most deposit energy at the edge of LS sphere. Vertex reconstruction algorithm in FPGA is difficult and need too much resource. So we can't reconstruct event vertex accurately online. But we can use another method to find the approximate event vertex.

In this method, we want to correct the PMT's first hit time by deducting photon's flying time in LS. Because the distribution of PMT's corrected first hit time is narrow, we can use this character to find the approximate event vertex. If we know the vertex of the event, we can know the photon's flying time from vertex to each PMT. So it is easy to correct the PMT's first hit time by deducting TOF(Time Of Fly).

But as mentioned before , it is difficult to find event vertex accurately by FPGA's algorithm online. So we divide the central detector volume into 179 5m×5m×5m cubic regions. We assume each region's center as a possible event vertex. For each event, we correct the PMT's first hit time for each possible event vertex in parallel.

As we have 179 cubic regions, we can get 179 distributions of corrected PMT's first hit time. If the region contain the true event vertex, the distribution of corrected PMT's first hit time will be most narrow. So we can find the region which contain the event vertex. And then using the center of the region as the approximate event vertex.

To demonstrate this method is viable, we simulated 4MeV positron generated at R=15m in central detector. Fig.3 show the PMT's first hit time without TOF corrected. Fig.4 show the PMT's first hit time with TOF corrected.

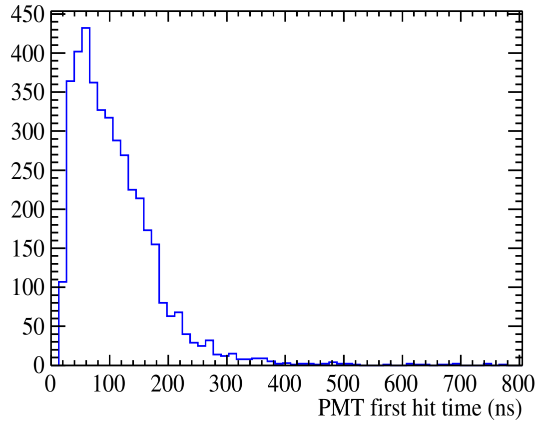

Fig. 3: PMT's first hit time without TOF corrected

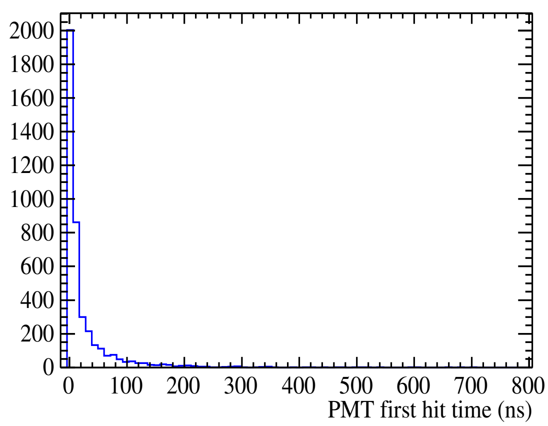

Fig. 4: PMT's first hit time with TOF corrected

From Fig.3 and Fig.4 we can see the distribution of PMT's first hit time is narrow when we do the TOF correction. So the width of distribution can be used to check if the TOF correction is valid.

With the reconstructed approximate vertex, we can set different radius threshold to reduce radioactivity backgrounds. In the trigger system, the first and secondary trigger system are in parallel. In the first trigger system, we record the events which the visible energy greater than energy threshold. In the secondary trigger system, we record the events which the visible energy less than energy threshold and the reconstructed vertex position less than radius threshold. In table.2 we show the central detector's sum radioactivity background rate on different energy and radius threshold.

Table 2: The sum radioactivity singles rates in central detector on different energy and radius threshold

Sum Radioactivity Single Rate(Hz)	E>0.1MeV	E>0.2MeV	E>0.3MeV	E>0.4MeV	E>0.5MeV	E>0.6MeV
R<10m	142.368	98.332	96.9047	95.9515	95.2811	93.7126
R<11m	153.808	99.1398	97.5285	96.4432	95.6678	93.8127
R<12m	199.79	102.354	100.039	98.4438	97.2644	94.2101
R<13m	249.897	105.33	102.395	100.341	98.7855	94.5798
R<14m	249.897	105.33	102.395	100.341	98.7855	94.5798
R<15m	289.921	112.385	107.156	103.627	101.128	95.4422
R<16m	458.269	148.923	131.168	119.73	112.381	99.866
R<17m	540.865	173.071	146.688	129.847	119.277	102.776

The promising secondary trigger system not only can reduce radioactivity background event rate, but also can reduce dark noise event rate.

In Fig.2 we can see if we set energy threshold below 0.3MeV, the dark noise event rate will be high. But in Fig.4 we can see the width of PMT's first hit time distribution is narrow when we do the TOF correction. If we find the approximate vertex of event, we can correct the PMT's first hitTime. And the width of PMT's first hit time distribution will be narrow. So we can reduce the trigger integration time from 300ns to 50ns. And then we can use the formula (1) to estimate the dark noise event rate, when trigger integration time is 50ns. The rescult is shown in Fig.5.

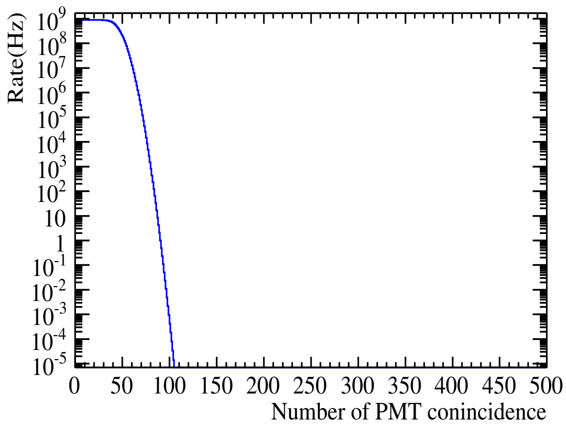

Fig. 5: Dark noise event rate when trigger integration time is 50ns

5 The event rate estimation of water pool

6 The event rate estimation of top tracker

References

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