The background of the JUNO calibration system

Feiyang[1,*], Yue Meng

Shanghai Key Laboratory for Particle Physics and Cosmology, Institute of Nuclear and Particle Physics (INPAC) and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

Abstract

Jiangmen Underground Neutrino Observatory (JUNO) is reactor neutrino detector with 20 kton liquid sctitillator as a target. The main goal of JUNO is to determine the neutrino mass hierarchy (MH) via precisely measurement of anti-neutrino oscillation spectrum. The measurement requires high energy resolution (3% at 1 MeV) and small uncertainty (less than 1%), which give a huge challenge to calibration system. The devices of calibration system close to the central detector will increase the background, which worsen the energy resolution and thereby lower the MH sensitivity. In addiction, the background will also deteriorate other neutrino spectrum like supernova neutrino, solar neutrino and so on. Well known background of calibration can help us do data analysis. In this paper, we demonstrate the method of calculation of background and the expected value for calibration system.

Keywords: JUNO, Calibration, background, radioactivity.

1. Introduction

Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment. The main goal of JUNO is to determine the neutrino mass hierarchy (MH) via precisely measuring reactor anti-neutrino oscillation spectrum.

The JUNO experiment is in Jiangmen city, Guangdong province, China, 53 km from Yangjiang and Taishan nuclear power plants (NPP). The target of JUNO is 20 kton liquid scintillator with 12 cm thickness spherical acrylic shell as container. The central detector is a 35.4 m diameter ball within a water pool.

*Corresponding author

The water pool a 40 m hight and 40 m diameter cylinder filled with ultra-pure water as a buffer to stop the external radioactivity and veto cosmogenic ray. There are about 18000 20-inch and 25000 3-inch photomultipliers (PMTs) in the water pool close to the central detector with about 75% coverage.

The reactor anti-neutrino could be detected and identified via so-called inverse beta decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. The positron will deposit energy first as a prompt signal, while the neutron will be captured by the nuclear (proton or carbon) within about 200 us as a delay signal. With the pair of prompt signal positron and delay signal neutron, the efficiency of IBD events selection could be significantly improved. However, the background of physics-like events will smear the prompt and delay signal, which will reduce the selection efficiency and data quality. Two physics-like events from background with interval time of about 200 us will be falsely identified as IBD events. And the extra introduced background events will distort the reactor neutrino spectrum, and thereby worse the neutrino MH sensitivity.

The background is mainly from cosmogenic and nature radioactive isotopes. In the LS, the interaction of energetic cosmic muons with C-12 will produce radioactive isotopes like Li-9, He-8, B-12 and so on. The radioactive isotope is not stable and will decay to emit alpha, beta and gamma particles. Especially for Li-9 and He-8, they can emit both a beta and a neutrino, just like a IBD signal, which will significantly influence the efficiency of IBD selection. The other background source, nature radioactive isotopes is from kinds of material used in the experiment. The isotopes mainly include U-238, Th-232, and K-40, which have long-lived time at billion years level. The radioactive material includes LS, acrylic, stainless steel, PMT and material from calibration system. In principle, the closer to detector, the more significant of background contribution to experiment. Since the part of calibration device is close and even in the central detector, so the background of calibration system contribution should be significantly treated.

Different from background of other system like LS, acrylic and PMT, the background from calibration system is position dependent. Since the location of background from calibration system is well known, a special volume cut is possible for data analysis. Besides, it can give a better background estimation with position dependent. In this paper, we will study the influence of calibration system on the JUNO experiment background, which consists of the following ingredients:

1. Introduction of JUNO calibration system.

2. Potential background and budget.
3. Measurement of radioactive material of calibration system.
4. Background contribution via MC simulation.
5. The influence on MH sensitivity.

2. JUNO calibration system

The JUNO calibration system is designed to mainly correct energy non-linearity and detector non-uniformity ,which requires the multiple sources and many locations to do calibration. To meet the requirement, the source should be deployed to certain position with cm level precision, which is big a challenge. So it's difficult to avoid contact with the LS region and even some components should be permanently in it. The calibration systems includes 4 deployment sub-systems as shown in Fig. 1 and 2 positioning sub-systems.

2.1. Automatic Calibration Unit (ACU)

The ACU is located at the top of the calibration house, which keep away from the central detector (CD). The touch with LS region only occur during the routine calibration. The routine calibration sources include laser source and radioactive source. The rate of laser source and radioactive source are respectively 50 Hz and 100 Hz. The only fact we should concern is whether the background rate of cable is enough high to affect the calibration data. Compared with the rate of source, the background rate is a small value which can be ignored.

2.2. Cable Loop System (CLS)

The strategy of CLS is to deploy the calibration sources offaxis position in vertical half-plane. There are two asymmetric CLSs designed as illustrated in Fig. 1. The calibration source is attached on central cable and side cable. A piece of 2.4 kg PTFE is permanently fixed on inner surface of acrylic shell to hold the side cable. During the calibration, both central cable and side cable is in LS region to deliver the source. And after the calibration, the central cable will be retracted while the side cable will stay in the CD. The length of cable in the CD is about 71 m, and the total mass is 0.269 kg. The core of the cable is stainless steel (SS), while the shell is PTFE. The CLS cable is stainless steel (SS) core and PTFE shell, and the diameter of cable is 1 mm, while the average density is 4.8 g/cm^3.

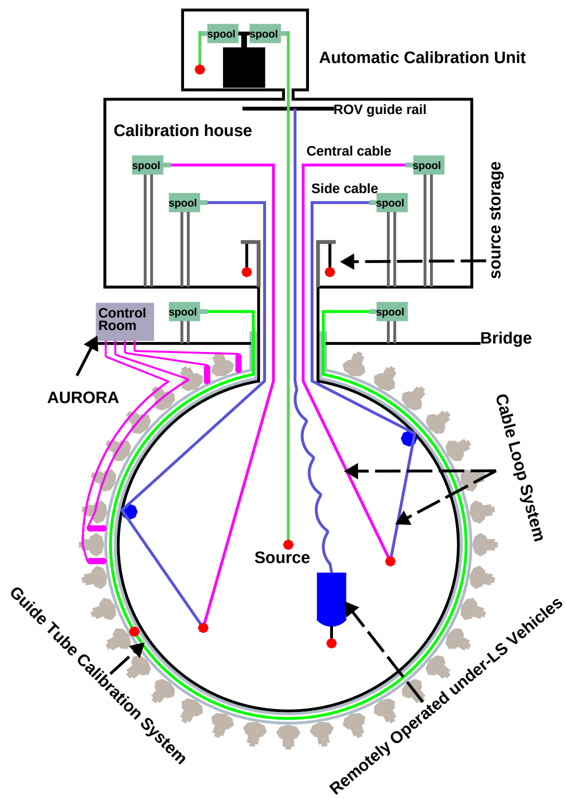

Figure 1: The overview of JUNO Calibration systems

2.3. Guide Tube Calibration System (GTCS)

The GTCS is a tube looped outside of the acrylic sphere along a latitude line, within which a radioactive source with cables attached to both ends gets driven around with good positioning precision. Ten sensors are used to determine the position of source. The PTFE tube, the cable and position sensor is close to the CD. Despite the GTCS is out of the CD, MeV-scale gammas can still easily penetrate the water and acrylic and deposit energy in the LS target. The background of their contribution is a non-negligible value and should be seriously studied.

2.4. Remotely Operated under-LS Vehicles (ROV)

ROV is designed to deploy the source in CD with a 3-D scanning. The ROV is not a routine calibration system, the frequency of ROV calibration is at one time per year level. And usually the device is in the calibration house, which is far away from the CD. So the background contribution of ROV can be negligible.

2.5. AURORA

2.6. USS

USS is an important component of JUNO calibration system. The system is permanently in JUNO central detector for calibration source position determination. To avoid the problem of multiple paths that will worse the precision of position measurement, the USS receiver will will be installed in the inner of CD, meaning that it will permanently contact with LS. Since the components of USS are in the LS of JUNO, it will introduce non-negligible background to the detector.

The radioactivity isotopes will emit MeV energy level particles (alpha, beta, gamma), which is in the energy range of physics events. These particles will enter to the detector and be detected, resulting signal disturbing the real physics signal, which is called background. So controlling the background of USS is a work for JUNO calibration. The USS includes cables, which is close the Acrylic inner sphere, with total length xx m, and 8 ultrasonic receivers, which is attached on acrylic shell. The USS cables consist of Teflon and stainless steel (SS), with diameter 1 mm. The line density is 0.01 kg/m. The ultrasonic receivers consist of two parts, NI and PCB with mass 0.106 kg.

2.7. CCD

CCD is an alternative choice for positioning system to cross check USS. CCD use 8 cameras in water pool to take photons for calibration source with led at bottom weight, and then with machine learning, we can resolve the position of calibration source based on the pixel of photons. Since the cameras is outside of CD and the distance from cameras to LS region is about ?? m, the corresponding contribution rate is only 0.04 mHz, which is a pretty small value.

3. Radioactive background

3.1. Potential background

The isotopes we should consider in background estimation include ^{238}U, ^{232}Th, ^{40}K, ^{137}Cs, Radon, and Kr. Among them, ^{238}U, ^{232}Th and ^{40}K are long-lived isotopes with billion years life time, so the rate of decay is stable within 20 years running. ^{238}U is one isotope of uranium in nature with a abundance of 99%. The life time of ^{238}U is about 4.47 $\times 10^9$ years. Besides ^{238}U decay, the daughter isotope is also not stable and will decay, which should be considered during the background calculation. And a series of daughter isotopes construct a decay chain. Beginning with naturally occurring ^{238}U, And life time of the daughter isotope is pretty short compared with ^{238}U. So in the equilibrium state of decay, the rate of every daughter isotope should be equal to the rate of ^{238}U decay. ^{232}Th is one isotope of thorium, with abundance almost 100%, life time 1.4 $\times 10^{10}$ years. Just similar to ^{238}U, ^{232}Th also has a decay chain. ^{40}K is one of potassium isotopes with life time 1.25 $\times 10^9$ years, abundance 0.012%. Different from ^{238}U and ^{232}Th, ^{40}K doesn't have decay chain.

Compared with ^{238}U, ^{232}Th and ^{40}K, the life time of ^{137}Cs ^{60}Co is pretty short with only several or several tens of years. For most material, the rate of them is too low to test, but they also should be considered if the rate is very high.

The emission particles from decay include gamma, beta and alpha, which is isotopes dependent.

1. isotopes: U,Th,K,Cs,Co, Radon, Kr.
2. decay: gamma, beta, alpha,
3. bulk: surface, emanation

3.2. Requirements and budget

The main background is from LS, The overall budget should be kept less than 0.2 Hz.

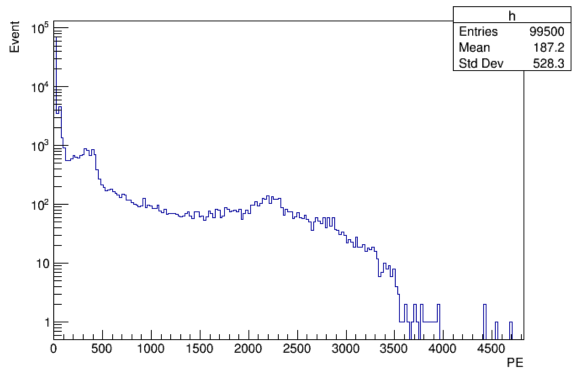

Figure 2: Simulation for ^{238}U in USS receiver

Calibration component location	Items
Inside CD (permanently)	USS receivers
Inside CD (permanently)	USS cable
Inside CD (permanently)	CLS cable
Inside CD (permanently)	Anchor and mounting structure
Inside CD (permanently)	Surface cleanliness
Radon emanation of the calibration house	ACU/CLS spool/ROV/Calibration house
Outside CD (permanently)	GT
Outside CD (permanently)	CCD
Outside CD (permanently)	AURORA

4. Simulation method, cut

4.1. Simulation method

SNIPER is an official tool to simulate JUNO experiment[1]. The basic geometry of detector is developed by JUNO software members, but not including all calibration related geometry. So first of all, the corresponding geometry should be constructed and written into the detector in correct position. And then assume the radioactive sources (^{238}U, ^{232}Th, ^{40}K) are uniformly distributed in the material. The simulation will run for every component independently. The spectrum of deposit energy in LS region is shown in Fig. 2.

Table 1: List of survival probability

System	Item	^{60}Co	^{238}U	^{232}Th	^{40}K
CLS	Cables	-	1.28	1.61	0.143
	Anchors	-	0.024	0.037	0.0031
GTCS	Tube	0.0123	0.0071	0.014	0.00104
	Cables	0.0117	0.0076	0.013	0.0012
	Sensors	0.0107	0.0082	0.0111	0.00072
USS	Cables	-	0.083	0.141	0.0132
	Receivers	-	0.024	0.038	0.0044
AURARO	Termination	-	2.8×10^{-6}	1.11×10^{-5}	1×10^{-7}

4.2. Energy and Fiducial volume cut

The MC simulation is used for calculating efficiency of radioactivity particles detected. However, the truth is that not all events have influence on selection of IBD events. Considering that the energy of prompt IBD signal is above 1 MeV. So one energy cut of 700 keV could basically remove the low energy events that won't affect the IBD spectrum.

Duo to the sharply increased background, poor calibration and bad vertex reconstruction at the boundary of detector, the quality of physics events at the boundary will decrease. To ensure the quality of physics events, 0.5 m cut will be carried out during calculation, which means that we only calculate the events with radius less than 17.2m (the radius of detector is 17.7m).

4.3. Survival probability

With given number of simulation events, a ratio of residual events with cut and the initial events can be calculated. Besides, since ^{238}U and ^{232}Th have multiple daughter nucleus, so the ratio should be multiply by 14 and 10 respectively for ^{238}U and ^{232}Th. The ratio is called survival probability, which is radioactive isotopes, positions and geometry dependent. The survival probability is one of the key points to reflect the importance to the detector background. And with known survival probability and material radioactivity, the background contribution to the detector could be calculated.

Table? shows the summary of survival probability of calibration system survival probability.

Analysis the results for each sub-systems ....

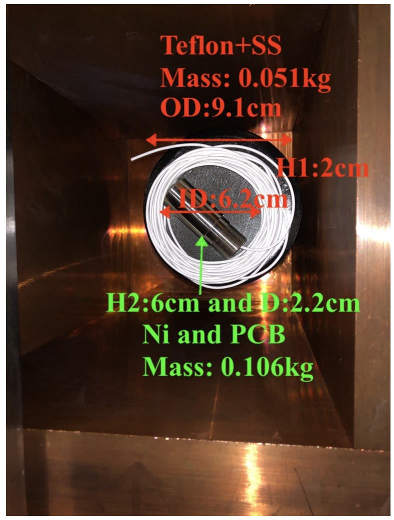

Figure 3: JUNO USS cables and receivers. They are in high pure germanium detector for radioactivity testing

5. Radioactivity measurement

To control the background from JUNO calibration system, we need to select pure material with low radioactivity to set up the calibration system. A high pure germanium (HPGe) detector located in Jinpin underground experiment is used to measure the radioactivity of the material as shown in Fig.3. The material of calibration system that has potential background should be measured with HPGe detector. Actually, most of material is selected with the lowest radioactivity in several candidates. Table 2 is list of the radioactivity of materials that have potential background contribution. Since the ^{232}Th and ^{238}U radioactivity can measured from two daughter isotope, so to be conservative, the maximum of the two value is used for calculation.

The measurement only shows radioactivity of material, but not for background rate. So we should use detector simulation to calculate the efficiency of background constribution, and thereby obtain the background rate.

6. Radioactive background result

6.1. Calibration systems

6.1.1. ACU

Since there are no component of ACU permanently in central detector, so the only concern about ACU background contribution is for calibration data.

Table 2: List of material raioactivity.

System	Item	^{60}Co		^{238}U		^{232}Th		^{40}K	
		mBq	Error	mBq	Error	mBq	Error	mBq	Error
CLS	Cables	-	-	6.3	4.6	0.3	0.3	3.3	2.3
	Anchors	-	-	0.07	-	0.20	0.04	1.91	0.08
GTCS	Tube	10.5	-	0.4	-	0.3	-	2370	50
	Cables	97	4	10	28	8	6	12	24
	Sensors	15	5	3420	370	3830	64	4946	385
USS	Cables	-	-	8.8	17.8	110.3	25.6	342.4	204.2
	Receivers	-	-	17.3	5.9	14.1	5.8	69.8	50.9
AURARO	Termination	-	-	26	-	174	-	288	-

The background is from mechanical cable for radioactive source and optical fiber for laser source. The background rates of mechanical cable and optical fiber are respectively ?? mHz and ?? mHz, negligible compared with the calibration source.

6.1.2. CLS

The mechanical cable of CLS and corresponding anchor will be permanently in CD. The contribution background of CLS is shown in Table ?.

The anchor is at the boundary of CD, contact with the acrylic inner surface, so with the fiducial volume cut, most of background event will be removed resulting low rate of contribution. However, based on the CLS design, most of mechanical cable is in the fiducial volume, so even with fiducial volume cut, it is still difficult to significantly decrease the background rate.

Table 3: List of CLS

Isotope	CLS cables		CLS anchors	
	Rate (mHz)	Err (mHz)	Rate (mHz)	Err (mHz)
^{238}U	8.06	5.89	0.0017	-
^{232}Th	0.48	0.48	0.0074	0.0015
^{40}K	0.47	0.33	0.0059	0.0002
Total (mHz)	9.01	5.92	0.0150	0.0015

Table 4: List of GTCS radioactivity

Isotope	PTFE tube		Cable		Sensor	
	Rate (mHz)	Err (mHz)	Rate (mHz)	Err (mHz)	Rate (mHz)	Err (mHz)
^{60}Co	0.130	-	1.135	0.047	0.161	0.054
^{238}U	0.003	-	0.076	0.021	28.044	3.034
^{232}Th	0.004	-	0.104	0.078	42.513	0.710
^{40}K	2.465	0.052	0.014	0.029	3.576	0.277
Total (mHz)	2.602	0.052	1.329	0.098	74.294	9.789

Table 5: List of USS

Isotope	Receiver		USS Cable	
	Rate (mHz)	Err (mHz)	Rate (mHz)	Err (mHz)
^{238}U	0.415	0.142	0.734	1.477
^{232}Th	0.536	0.220	15.552	3.610
^{40}K	0.307	0.224	4.520	2.695
Total (mHz)	1.258	0.345	20.806	22.477

6.1.3. GTCS

6.1.4. USS

6.1.5. AURARO

6.2. Influence to total JUNO background

The total rate of background from calibration system is about ?? mHz, which meet the required budget.

7. Conclusion

With HGe detector, we have tested the radioactivity all the material from calibration system. And with geant4-based detector simulation, we have calculated the rate of background with energy and fiducial volume cut. The total rate is less than ?? mHz, which meets the requirement. The degeneration of MH sensitivity due to calibration system background is about ??.

8. Acknowledgement

References

References

[1] Lin, Tao et al., J.Phys.Conf.Ser. 898 no.4, 042029, arXiv:1702.05275 (2017)

Table 6: List of AURARO

Isotope	Receiver		Electrical cable	Optical fiber
	Rate (mHz)	Err (mHz)	Rate (mHz)	Rate (mHz)
^{238}U	7.28×10^{-5}	10^{-5}	-	-
^{232}Th	1.93×10^{-3}	1.2×10^{-4}	0.04	0.001
^{40}K	2.88×10^{-5}	2×10^{-5}	-	-
Total (mHz)	0.002	0.0001	0.04	0.001

Table 7: List of summary

System	Item	Rate (mHz)	Err (mHz)
CLS	cable	9.01	5.92
	anchor	0.015	0.0015
GTCS	tube	2.602	0.052
	cable	1.329	0.098
	sensor	74.294	9.789
USS	receiver	1.258	0.345
	cable	20.806	22.477
CCD	camera	0.04	-
AURARO	termination	0.002	0.0001
	cable	0.040	-
	fiber	0.001	-
Total		109.397	25.223