PREPARED FOR SUBMISSION TO JINST

N[TH] WORKSHOP ON X
WHEN
WHERE

JUNO calibration strategy

Feiyang Zhang,[a] **Jianglai Liu,**[a]

[a]*School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai Key Laboratory for Particle and Cosmology, Shanghai, 200240, China*

E-mail:

ABSTRACT: Jiangmen Underground Neutrino Observatory (JUNO) is a spherical-tank (35.4 m diameter) neutrino detector filled with 20 kton liquid scintillator. It is located 2?? m underground (700 m water equivalent) in Jiangmen City, Guangdong province, China. The primary purpose of JUNO is to determine the neutrino mass hierarchy (MH). So a high physics requirement is purposed for energy resolution and energy scale. The overall energy resolution should be better than 3% and uncertainty of energy scale should be less than 1%. In order to achieve this physics requirement, a calibration strategy is purposed. The calibration strategy including types of source, geometries of design, simulation and expected results are presented in this paper.

KEYWORDS: JUNO,Calibration,Simulation

---

[1]Corresponding author.

Contents

1 Introduction

1.1 Motivation of calibration

Since the main purpose of JUNO is to determine the neutrino mass hierarchy, we should precisely measure the IBD spectrum. Based on this, the energy resolution of JUNO detector should be better enough and also we need to have a better understand of energy resolution and energy non-linearity of the detector.

However, due to the LS transmittance and total reflection at CD boundary, connection bar and so on, the response of detector is not uniform, and the non-uniformity effect will worsen the detector energy resolution, so we need to correct the non-uniformity with calibration system to make the energy resolution good enough to meet the physics requirement. And then we also need a good understand of energy resolution. The energy resolution is energy dependent, not only include statistic effect, so we need various calibration sources to calibration it.

The other effect is about energy non-linearity of detector response. The energy scale is also energy dependent. Since the incorrect energy scale will give wrong MH sensitivity (increase or decrease), so we need various source to calibration it.

1.2 Calibration system

The deployments systems of calibration sources include ACU, CLS, GT, ROV. For ROV and CLS, we have independent positioning system.

1.2.1 Automatic Calibration Unit (ACU) system

The ACU is developed to do calibration along the central axis of CD, which is very similar to ACU of Daya Bay experiment. As illustrated in Figure, there are 4 spool installed on the turntable. Three routine sources and one exchangeable source are installed on the ACU. The three routine source include one gamma source (K40), one neutron source (Am-C) and one laser source.

1.2.2 Cable loop system (CLS)

The CLS mainly consist of two cables, side cable and central cable. Controlling the lengths of two cable, we can deploy the sources to scan one vertical plane area, as illustrated in figure ?. In order to increase the scanning area, we have two set of CLS with different ancho position (48, 780).

1.2.3 Guide Tube (GT)

Since the source cannot reach some boundary area of CD duo to mechanical limit, a Guide Tube calibration system was purposed. The guide tube will be out of CD. With the GT, we can position the calibration source along the surface of CD to have a better understand of boundary effect.

1.2.4 Remotely Operated Under-liquid-scintillator Vehicles (ROV)

ROV is 3D scanning system, meaning that we can move the calibration to nearly everywhere in the CD.

1.2.5 Positioning system

It's difficult to determine position of source based on length of cable. Due to self-weight, the cable is not straight, we cannot calculate the position of source with naive trigonometric relation. So it's necessary to use independent position system to determine the source position. The requirement of precision of source position is 3 cm compared with that the requirement of vertex reconstruction is 10 cm.

2 Calibration source

The radioactive sources include routine gamma and neutron sources. The detail of calibration sources and correlated energy is shown in table ?

2.1 source geometry design

Design of gamma sources, as you can see the figure ?, the internal part is stainless steel to seal the source. Both diameter and height of the SS are 6mm, which is very small to decrease the energy loss, with two loops at top and bottom to attach the cable. The outer is the PTFE shell to increase the reflectivity to minimize the photon loss.

ii. Design of neutron sources, as you can see figure ?. The size of neutron source is 8ÃŮ8 mm, since the smaller neutron source is not safe and necessary. Figure ? shows the prototype of neutron source which has been tested in Daya Bay Detector.

2.2 simulation with source geometry

To study the effect of photon loss and energy loss, simulation of calibration source was done with JUNO official software SNIPER, developed based on geant4. The geometry of sources has already been written into SNIPER as shown in figure for both gamma and neutron source. The figure ? shows the simulation of gamma source 137Cs with source enclosure. The Compton tail due to energy loss in source geometry will shift the full absorption peak. The fit function will correct the shift. The figure ? shows the simulation of neutron source Am-C with source enclosure. Even with source enclosure, there is still no Compton shoulder for neutron source.

3 Calibration simulation

3.1 Uncertainty of calibration

3.1.1 Shadowing effect

The material of source container shell is Teflon. Even the reflectivity is very high (assume 90% reflectivity in the simulation), there still must be some optical photon loss. So we need to study the shadowing effect. To decouple the shadowing effect and Compton effect, we can select the events without energy loss during the simulation. With the cut, the PE spectrum follows the Gaussian distribution, so we fit it with Gaussian function to obtain mean value as you can see figure 1. And then compare it with the ideal case, bare source without enclosure.

3.1.2 Compton effect

The Compton effect is due to energy loss in non LS material, and this will introduce Compton shoulder in PE spectrum. And the Compton shoulder will shift the mean value. There are several functions used to fit the spectrum correct the effect. However, even correcting it, there still be some uncertainty. We will consider two common functions, crystal ball function, electromagnetic calorimeter function.

3.1.3 Electronic effect

The non-linearity of electronic can be corrected to 0.3% uncertainty level with laser calibration system. Here we assume the residual non-linearity is energy dependent, Erec/Evis = 1 + Îś*exp(-Evis/t), t = 2.55 MeV

3.1.4 Statistical effect

3.2 Energy scale

One of main purpose of JUNO calibration is to make uncertainty of the scale less than 1%. In order to reach this physics requirement, we should have a better understanding of the energy non-linearity of detector response. A series of radioactive sources will be used to do the calibration of energy non-linearity, including gamma sources, neutron source and beta source.

Here we will introduce the strategy of JUNO calibration based on MC simulation result. The full absorption peak of delay signal of neutron capture at Hydrogen (2.22 MeV) is determined as the energy scale. Then we can reconstruct energy of other calibration source with PE/scale. The reconstructed energy is different from true energy due to energy non-linearity. The ratio of reconstructed energy and true energy will be described as energy dependent of non-linearity. Figure show the energy non-linearity of gamma from 0.511 MeV to 6.13 MeV, which can be obtained from calibration system.

However, IBD events is positron events. So we would like to know the response of positron energy non-linearity. The relation between gamma and electron can be established with geant4. And we assume that electron and positron have almost same action of energy non-linearity in addition to two gammas from positron annihilation. There are mainly three physics process for the conversion from gamma to electron, including pair production, Compton scattering, photoelectric effect. Figure ? shows the probability density function (PDF) of energy of electron with initial energy of gamma 6.13 MeV. In the geant4 simulation, we can obtain the truth information of energy deposit. The energy of primary electron from initial gamma or gamma from positron annihilation will be recorded as figure ?. The electrons recorded construction PDF of electron energy shown in figure?.

Referring to Daya BayâĂŹs method, an empirical formula with 4 parameters was used to describe energy non-linearity of electron, Evis/Etrue = (p0+p3Etrue)/(1+p1*exp(-p2Etrue)). The energy non-linearity of gamma can be deduced with both the empirical formula and the PDF of electron energy.

The data of gamma energy non-linearity can be obtained from calibration. With the model we have established, we can fit the data to extract the parameters. Then we get the non-linearity of electron. The only different between electron and positron is annihilation gamma. And this effect can be calibrated with Ge68, ignoring annihilation in flight. The figure ? shows the result of fitting with the model of non-linearity gamma non-linearity.

Systematic uncertainty analysis

3.3 Energy resolution

3.3.1 Non-unioformity correction

With calibration system of CLS, sources can be deployed in one vertical plane. Assuming the response of detector is phi symmetrical, we can do the non-uniformity correction with the vertical calibration mapping. The calibration mapping is shown in figure ?. We use one thin plate spline function to fit the data to describe the mapping. The function shows the Corresponding ratio to CD center. With algorithm of vertex reconstruction, we can get the energy and vertex of IBD events. Then we can correct the non-uniformity by scaling it to CD center. Then we do simulation to qualify the non-uniformity. The mono energy positron uniformly generates in CD. Figure ? shows the energy spectrum of positron, which shows bad energy resolution. Then with the calibration mapping, we can correct it. Figure ? is the energy spectrum after correction, showing better energy resolution with fiducial volume cut R < 17.2 m. We fit the spectrum with Gaussian function to obtain full absorption peak and sigma, then energy resolution can define as sigma/mean. So we use the energy resolution to qualify the non-uniformity correction.

Determination of anchors position. In order to maximize scanning area of calibration, we try to use two asymmetrical CLSs to deploy the source. Therefore, we need to determine the positions of two anchors. Due to self-weight, the cable is not straight, so the source cannot be deployed to the boundary of detector. And in this study, we naÃŕvely assume the slope angle of cable is 100 as you can see the figure. Vary the two anchor position, we construct different calibration mappings. Then calculate the corresponding energy resolution. Figure? Shows the energy resolution as function of anchor positions. From the calculation, we get the best choice of anchor position (48,78) corresponding minimum energy resolution 2.?%.

Basic source coverage. In the realistic experiments, itâĂŹs impossible to use infinite points to do calibration. We purpose to do the CLS calibration monthly, and to avoid affect the norm physics data taking, the monthly calibration time should be limited to about 1 days. So the inner calibration points are 240, including 21 with ACU and 219 with CLS. We randomly select 219 points from a mount of points, and then calculate the corresponding energy resolution. Repeat the selection many times and then get the distribution of energy resolution. Choose the best selection with minimum energy resolution. The figure ? shows distribution of energy resolution. Figure ? shows relative best choice of calibration points.

Systematic uncertainty analysis. Vertex reconstruction. The non-uniformity correction is based on vertex of events, so vertex reconstruction significantly affects the quality of non-uniformity correction. Here we assume resolution of vertex reconstruction vary from 5cm to 50 cm. Figure 5? Shows the energy resolution as function of resolution of vertex reconstruction.

Positioning smearing. Due to self-weight of cable and friction, itâĂŹs difficult to determine position of source only based on length of cable. So an independent positioning system was purposed. In order to study the influence of uncertainty of source position, we vary the uncertainty from 1 cm to 5 cm to do the non-uniformity correction respectively. The figure ? shows energy resolution as function of uncertainty of source position.

3.3.2 Calibration of energy resolution

The non-uniformity correction will improve energy resolution. However, in order to obtain high sensitivity of MH, itâĂŹs essential to exactly know what energy resolution of detector is. So calibration of energy resolution is indispensable.

Energy resolution of gamma. Since we mainly use gamma source to do calibration, it easy to obtain gamma energy resolution. However, there is much difference between energy resolution of gamma and positron even with same reconstructed energy. So we need to develop an algorithm to derive energy resolution of positron from that of gamma.

Relationship between gamma and electron about energy resolution Very similar to non-linearity correction, but it is a hash table other than PDF to describe the relationship between gamma and electron. Assume energy resolution of positron satisfies:

And reconstructed energy and uncertainty of annihilation gammas (2ÃŮ0.511 MeV) are respectively E0 and ÏČ0, which can be obtained calibration source Ge68. The annihilation gammas are the only difference for electron and positron with same kinetic energy. So we can get that:

The energy resolution of electron can be written as With this formula of electron energy resolution and the hash table between gamma and electron, we can establish model of gamma energy resolution with only parameters a and b.

Model of gamma energy resolution. The uncertainty of gamma reconstructed energy could be divided into two parts. One is due to non-linearity of electron and the other is from uncertainty of electron reconstructed energy. For the non-linearity effect, we still use Evis/Etrue = (p0+p3Etrue)/(1+p1*exp(-p2Etrue)) to describe. With hash table, we can get the overall mean of reconstructed energy:

The subscript i and j are event number and index of energy. N is total events of sample from genat4. M is number of electron from the conversion of gamma to electron. M is constant value, dependent on event number. So we can calculate the uncertainty from non-linearity effect:

For the uncertainty of electron reconstructed energy, since gamma uncertainty is composed of that multiple electron, we can add all uncertainty of electron to get the uncertainty of gamma as below:

Then we get the overall energy resolution of gamma:

Fit to get energy resolution Since energy resolution of gamma can be obtained with calibration system, then we can fit the data with the model to extract the corresponding parameters a and b. The figure ? show the result of fitting.

Systematic uncertainty analysis.

Energy resolution at CD center. The energy resolution of gamma will be affected by statistic, source enclosure and non-linearity. i. Statistic ii. Source enclosure iii. Shadowing effect

Energy resolution of detector. With calibration system, the energy resolution can only be calibrated point by point, however, IBD events are uniformly distributing in CD. So actually what we need to understand is the whole detector energy resolution. In order to achieve this physics requirement, we need to derive the detector energy resolution based on finite calibration points.

4 Calibration schedule

5 Conclusion

A Some title

Please always give a title also for appendices.

Acknowledgments

This is the most common positions for acknowledgments. A macro is available to maintain the same layout and spelling of the heading.

Note added. This is also a good position for notes added after the paper has been written.

References

[1] Author, *Title*, *J. Abbrev.* **vol** (year) pg.

[2] Author, *Title*, arxiv:1234.5678.

[3] Author, *Title*, Publisher (year).