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Calibration Strategy of the JUNO Experiment

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The Jiangmen Underground Neutrino Observatory (JUNO) will be the world's largest liquid scintillator (LS) detector to probe multiple physics goals, including determining the neutrino mass ordering, measuring solar neutrino, detecting supernova neutrino, etc. With an unprecedented 3% effective energy resolution and an energy nonlinearity better than 3% requirement to determine the neutrino mass ordering, the calibration system, including Auto Calibration Unit (ACU), Cable Loop System (CLS), Guide Tube Calibration System (GTCS), and Remotely Operated Vehicle (ROV), is designed with deploying multiple radioactive sources in various locations inside/outside of the central detector (CD). The strategy of the JUNO calibration system has been optimized based on Monte Carlo simulation results from calibration sub-systems data. This talk will present details of calibration strategy, including the JUNO calibration system design and simulation results, which help achieve an excellent energy resolution better than 3% between 1 MeV and 8 MeV.

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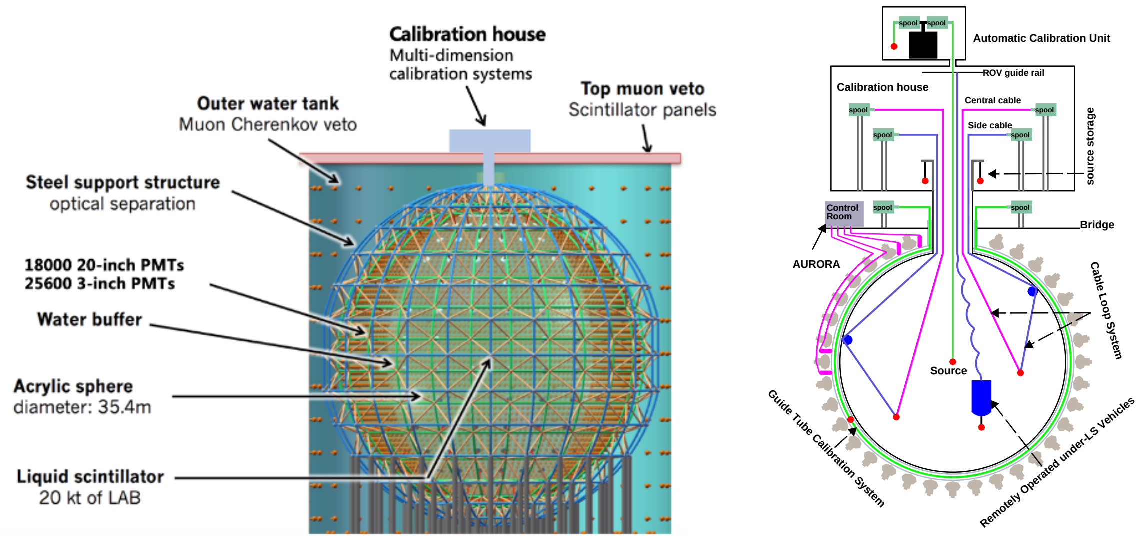
[*] Speaker

1. Introduction of JUNO

JUNO [1] has a rich program in neutrino physics and astrophysics, including determining the neutrino mass ordering, measuring oscillation parameters with geo-neutrinos and atmospheric neutrinos, detecting solar neutrinos and supernova neutrinos. For the primary goal of neutrino mass ordering determination, the sensitivity can reach 3σ within 6 years data taking.

The JUNO detector sketch is shown in Fig. 1a. 20 kton liquid scintillator will be filled into an acrylic sphere with a diameter of 35 m. The signal coming from neutrino interactions can be observed by 17612 20-inch photomultipliers (LPMT) and 25600 3-inch photomultipliers (SPMT). A Water Pool (WP) and plastic scintillator Top Tracker (TT) are used to veto muon induced background. A multi-dimension calibration system is designed and developed to understand the detector response [1]. Keys for the JUNO detector to determine the neutrino mass ordering are a better than 1% energy linearity and a 3% effective energy resolution for the JUNO central detector.



(a) JUNO detector **(b)** Calibration system

Figure 1: The layout of the JUNO detector and calibration system [2]

2. Calibration System

Multiple calibration sources and multiple dimensional scan systems (Fig. 1b) have been developed to correct the energy non-linearity and spatial non-uniformity of the detector response.

For a one-dimensional scan, the Automatic Calibration Unit (ACU) can deploy multiple radioactive sources or a pulsed laser diffuser ball along the central axis of the central detector [3–5]. For two-dimensional scan, the non-uniformity of the detector response can be acquired by off-axis calibration. A calibration source attached to a Cable Loop System (CLS) can be moved on a vertical half-plane [6]. Two sets of CLSs will be deployed to provide a 79% effective coverage on an entire vertical plane. A Guide Tube (GT) surrounds the outside of the CD and a source runs in a

Table 1: The radioactive sources and radiation types

Source	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

longitudinal loop to calibrate CD boundary effect [7, 8]. For a three-dimensional scan, a source attached to a Remotely Operated under-LS Vehicle (ROV) can be deployed to the desired locations inside the LS to investigate spatial non-uniformity [9]. Multiple gamma and neutron sources in Table. 1 are used in these scan systems.

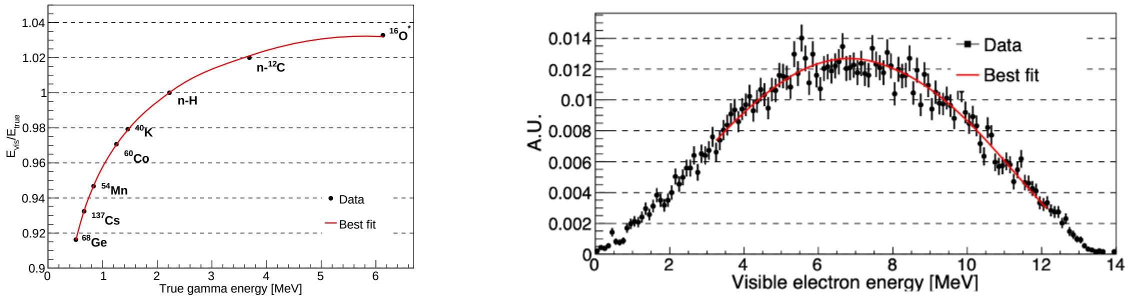
There are auxiliary devices for the calibration system, including positioning systems with an ultrasonic sensor system (USS) [10] and CCDs, an air-tight stainless steel calibration house where the ACU, CLS and ROV systems locate, and a light properties monitoring system AURORA (An Unit for Researching Online the LSc tRAnsparency).

3. Calibration Strategy

A comprehensive calibration strategy is developed to achieve an effective energy resolution better than 3% between 1 MeV and 8 MeV, and energy scale uncertainty < 1%. The physical non-linearity, induced by quenching effect in the liquid scintillator and Cerenkov photons emission can be calibrated by multiple gamma sources (Fig. 2a) and cosmogenic background ^{12}B (Fig. 2b). Finally, the instrumental non-linearity can be calibrated by combining dual calorimetry which includes LPMTs and SPMT, and tuneable laser source, and the residue bias after correction is less than 0.3%.

There are systematic uncertainties which are discussed below. (1) The uncertainty of shadowing effect, which is induced by absorption of Teflon capsule of radioactive sources, is less than 0.15% [11]. (2) The residue biases of energy loss due to stainless steel and Teflon capsule can be controlled to 0.1%. (3) 6.13 MeV gamma peak from $^{214}\text{Am} - ^{13}\text{C}$ is mixed with neutron-proton recoil energy causes 0.4% bias for this high energy end. (4) Instrumental non-linearity from LPMT and electronics can be corrected and residual non-linearity are control less than 0.3%. (5) The non-uniformity correction for positron is optimized to 0.3%. The combined systematic uncertainty is 0.7% for all energy range, which is better than 1% requirement. The non-linearity residues bias are shown in Fig. 3.

An energy resolution and an effective energy resolution are defined in Equation 1 and 2. In these equations, a term is the statistical term, b is a constant term dominated by position non-



(**a**) Gamma non-linearity (**b**) Cosmogenic background ^{12}B

Figure 2: JUNO calibration system non linearity and bias calibration effect

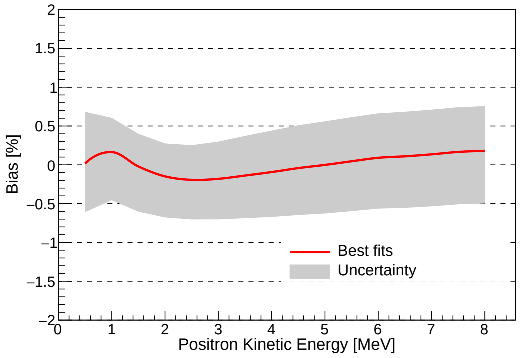


Figure 3: Non-linearity residue bias

uniformity, and c term represents the contribution by a background noise. Simulated neutrino energy spectra were generated assuming different values of a, b and c to investigate the impact of the energy resolution. 3% effective energy resolution can be achieved considering different scenarios.

$$\frac{\sigma_{E_{\rm vis}^{\rm prompt}}}{E_{\rm vis}^{\rm prompt}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}^{\rm prompt}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}^{\rm prompt}}\right)^2} \tag{1}$$

$$\tilde{a} = \sqrt{a^2 + (1.6 \times b)^2 + (\frac{c}{1.6})^2} \tag{2}$$

4. Calibration Program

The envisioned calibration program is listed in Table. 2. The weekly calibration is used to monitoring gain change of PMTs and neutron response. Monthly calibration is targeted to understand stability for both central axis and off-axis detector. A comprehensive calibration program will allow to fully map the energy non-linearity and non-uniformity with gamma and neutron sources.

Table 2: The envisioned calibration program

Program	Purpose	System	Duration [min]
Weekly calibration	Neutron (Am-C)	ACU	63
	Laser	ACU	78
Monthly calibration	Neutron (Am-C)	ACU	120
	Laser	ACU	147
	Neutron (Am-C)	CLS	333
	Neutron (Am-C)	GT	73
Comprehensive calibration	Neutron (Am-C)	ACU, CLS and GT	1942
	Neutron (Am-Be)	ACU	75
	Laser	ACU	391
	^{68}Ge	ACU	75
	^{137}Cs	ACU	75
	^{54}Mn	ACU	75
	^{60}Co	ACU	75
	^{40}K	ACU	158

5. Summary

A multi-dimensional calibration system was designed and produced. With various gamma and neutron sources, cosmogenic ^{12}B, in combination with a pulsed UV laser, the nonlinear energy scale of the positrons can be determined to a sub-percent level within the entire energy range of the IBDs. The calibration strategy is demonstrated to achieve JUNO physics goals with energy linearity better than 1% and an effective energy resolution of 3% for JUNO.

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