The development of 222Rn detectors for JUNO prototype (Postprint)

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Abstract

The radioactive noble gas 222Rn, which can be dissolved in water, constitutes an important background source for JUNO. In this paper, based on the water system of the JUNO prototype, two types of high-sensitivity radon detectors have been proposed and validated. The Si-PIN Rn detector, which employs a Si-PIN photodiode to detect -214Po, achieves a sensitivity of 4.2 mBq/m3, while the LS Rn detector, which utilizes a liquid scintillator to detect the coincident signals of -214Bi and -214Po, achieves a sensitivity of 34.4 mBq/m3. Both types of Rn detectors have the potential to be developed into online Rn concentration monitoring equipment for the JUNO veto detector.

Full Text

Preamble

Development of ^{222}Rn Detectors for JUNO Prototype

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Abstract

The radioactive noble gas ^{222}Rn, which can be dissolved in water, represents an important background source for the Jiangmen Underground Neutrino Observatory (JUNO). In this paper, we propose and validate two types of high-sensitivity radon detectors based on the JUNO prototype water system. The Si-PIN radon detector, which uses a Si-PIN photodiode to detect particles from ^{21} Po decay, achieves a sensitivity of approximately 4.2 mBq/m^3. The liquid scintillator (LS) radon detector, which uses liquid scintillator to detect coincident signals from -^{21} Bi and -^{21} Po decays, achieves a sensitivity of approximately 34.4 mBq/m^3. Both detector types show potential for development into online radon concentration monitoring equipment for the JUNO veto detector.

Keywords: Radon, Si-PIN, Liquid Scintillator

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment designed to determine the neutrino mass hierarchy and precisely measure oscillation parameters by detecting reactor neutrinos from the Yangjiang and Taishan Nuclear Power Plants. The experiment employs a 20-kiloton liquid scintillator (LS) detector with unprecedented 3% energy resolution (at 1 MeV) located 700 meters underground. To suppress radioactivity from surrounding rock and tag cosmic muons, the outer region of the central detector is filled with ultra-pure water and equipped with approximately 2,000 microchannel plate photomultiplier tubes (MCP-PMTs, 20 inches) to form a water Cherenkov veto detector. Consequently, strict requirements are imposed on radioactivity levels in the water. The natural radioactive noble gas radon (Rn), which is soluble in water, constitutes one of the most important background sources. According to Monte Carlo simulations for JUNO experimental requirements, the radon concentration in water should be better than 0.2 Bq/m^3 [1].

[Figure 1: see original paper] The JUNO prototype detector.
[Figure 2: see original paper] The conceptual scheme of water system for JUNO prototype.

Given the specific requirements of each subsystem, a prototype detector was proposed to test key technical issues and study radon properties. As shown in Fig. 1, an acrylic sphere located at the center of a stainless-steel tank (SST) serves as the LS vessel and is viewed by 51 PMTs immersed in pure water. The PP/Lead layer is designed to provide 1 meter water-equivalent shielding to reduce external radioactivity.

To maintain good water quality over extended periods, a reliable ultra-pure water purification and circulation system is necessary; its conceptual scheme is shown in Fig. 2. To measure radon concentrations at the ~0.2 Bq/m^3 level in the JUNO prototype water system, we have proposed and validated two types of high-sensitivity radon measurement systems.

2. Experimental Setup for Radon Measurement System

[Figure 3: see original paper] The scheme of Rn measurement system.

As a first step toward monitoring radon concentration in water, integration of the radon measurement system with the water system must be achieved. Fig. 3 shows a schematic view of the radon measurement system, which consists of four main components: (A) An atomizer, which serves as a water-vapor equilibrium device, transforms dissolved radon gas from water into air during flow. (B) A gas pipeline consisting of a drier, mass flow controller, and pump, which reduces gas humidity, controls flow rate, and transfers sample gas to measurement devices. (C) A monitoring system comprising a pressure gauge, thermometer, and hygrometer to track experimental conditions. (D) A measurement system consisting of the Si-PIN chamber and LS chamber for determining radon concentration.

To prevent contamination from environmental air, knife-edge flanges with metal gaskets and VCR pipelines with metal gaskets are used to ensure a leak rate of less than 1×10   ml/s.

The Si-PIN radon detector operates on the principle of electrostatic collection of ^{222}Rn daughter nuclei and energy measurement of decay   particles using a Si-PIN photodiode [2, 3]. The LS radon detector, in contrast, exploits radon' s high solubility coefficient in liquid scintillator; photons produced by   and   particles in the ^{222}Rn decay chain are detected by PMTs. Furthermore, the 164.3 μs half-life of ^{21} Po enables background suppression through coincident detection of -^{21} Bi and -^{21} Po signals.

2.1. Setup for Si-PIN Radon Detector

The Si-PIN radon detector comprises a cylindrical electro-polished stainless steel vessel, a cylindrical high-purity oxygen-free copper vessel, and a Si-PIN photodiode. The copper vessel measures 38 cm in diameter and 27.3 cm in height. A positive high voltage applied to the copper vessel generates an electric field that collects positively charged ^{222}Rn daughters on the Si-PIN surface, where decay   particles are subsequently detected [4]. The Si-PIN photodiode is a Hamamatsu S3204-09 with dimensions of 18 mm × 18 mm; its window has been removed to reduce energy loss as particles strike the photodiode [5]. An ORTEC 142A preamplifier [6] provides bias supply and signal readout. Before pulse recording by the oscilloscope (LeCroy 610Zi, 250 MHz sampling frequency, 20 μs readout window [7]), the signal is amplified 50 times by an ORTEC 671 amplifier [8].

2.2. Setup for LS Radon Detector

The LS radon detector consists of an acrylic cylinder and two PMTs. The acrylic cylinder measures 78 mm in diameter and 20 mm in height and is filled with liquid scintillator. Two 9821QB PMTs [9] from Electron Tubes company directly face opposite sides of the cylinder. Coincident signals from -^{21} Bi and -^{21} Po are used for both background suppression and radon concentration calculation.

[Figure 4: see original paper] Readout diagram of the LS Rn detector.

Fig. 4 shows the electronics scheme of the LS radon detector. Signals from the two PMTs are split into two paths by a quad linear Fan-in/Fan-out (FIFO, CAEN N625): one path goes to the oscilloscope (OSC) for pulse recording, while the other forms the trigger. The output pulse widths of the discriminator (DIS, CAEN N844) and logic unit (AND, CAEN N455) are both 100 ns. The first pulse from AND1 is delayed by 200 ns and broadened to 300 µs by a dual timer (DUAL, CAEN N93B). The coincidence of AND1 and DUAL is sent to the 500 µs time-window oscilloscope as a trigger signal. To suppress accidental coincidence background, the single-channel threshold is set to ~80 keV. [Figure 5: see original paper] shows an example pulse of a radon signal.

3. Optimization and Calibration

When ^{222}Rn and its daughters are in equilibrium, the ^{222}Rn concentration is proportional to the observed decay rates of or particles from its daughters. The event rate of ^{21} Po is used to calculate radon concentration because no other sources exist in its signal region [10] and ^{21} Po is known to have higher collection efficiency than ^{21} Po [11]. For the LS radon detector, coincident signals from -^{21} Bi and -^{21} Po are used for ^{222}Rn concentration calculation.

To establish the relationship between counting rate and ^{222}Rn concentration, a gas-flow solid radon source is used for detector calibration. When gas flows through the source at 1 liter/min, the radon concentration in the output gas, measured by RAD7 [12], is 84.80 ± 4.55 Bq/m^3. This output gas is used to calibrate both detector types.

3.1. Si-PIN Rn Detector Optimization and Calibration

To select the optimal bias voltage for the Si-PIN photodiode, a ^{21} Am/^{23} Pu hybrid source is used to study its energy response. Fig. 6 shows the dependence of energy response and resolution on applied bias voltage, indicating stable performance across various bias voltages. Based on the datasheet [5], 60 V is selected for subsequent calibrations and measurements.

A calibration factor (Cf) is defined in Equ. 1:

Cf [(counts/h)/(Bq/m^3)] = measured ^{21} Po signal rate / ^{222}Rn concentration

where the numerator is the measured ^{21} Po signal rate on the Si-PIN photodiode in counts/h, and the denominator is the ^{222}Rn concentration in Bq/m^3. The initial Cf value is derived from the observed ^{21} Po counting rate and the well-measured radon gas using calibration data. Fig. 7 shows the energy spectrum from the radon source; the energy region of ±4 around the ^{21} Po peak is used to calculate Cf.

[Figure 8: see original paper] CF dependence with supplied high voltage.

As described in Sec. 2.1, high voltage must be applied to the oxygen-free copper vessel to generate the electric field for collecting ^{222}Rn daughters. The high voltage value affects collection efficiency, causing Cf to vary with different voltage settings. To determine the optimal value, the relationship between Cf and applied high voltage was measured, as shown in Fig. 8. The Cf increases with high voltage. Considering detector stability and collection efficiency, 1500 V is preferred, yielding Cf = 26.38 ± 0.66 (counts/h)/(Bq/m^3) for background measurement. The uncertainty is statistical only.

3.2. LS Rn Detector Calibration and MC Simulation

[Figure 9: see original paper] The geometry constructed by the program.

Liquid scintillator has been used for radon measurement for many decades due to its strong radon enrichment capability and excellent properties as an experimental target. As described in Sec. 3, the counting rate of coincident -^{21} Bi and -^{21} Po signals can be used to calculate radon concentration.

To study energy deposition of -^{21} Bi in LS, a Monte Carlo (MC) simulation using Geant4, based on the Daya Bay simulation code, was constructed. Fig. 9 shows the geometry of the LS radon measurement chamber. The simulation includes effects of LS vessel geometry, ^{21} Bi distribution in LS, and electronic response. The simulated and measured -^{21} Bi energy spectra are shown in Fig. 10, showing good agreement. Differences in the lower energy region are caused by threshold effects and detection efficiency.

[Figure 10: see original paper] Left: Simulated spectrum of -^{21} Bi. Right: Measured spectrum of -^{21} Bi.

[Figure 11: see original paper] The time difference between -^{21} Bi and -^{21} Po.

To test the accuracy and efficiency of the electronic trigger shown in Fig. 4, the time difference between -^{21} Bi and -^{21} Po signals was calculated. The distribution of time differences and fitting results are shown in Fig. 11. The measured data agree well with theoretical expectations, indicating that the LS system is an effective radon concentration measurement system.

For the LS radon detector, Cf is defined slightly differently: the numerator in Equ. 1 becomes the counting rate of coincident signals. Using the same radon source as for the Si-PIN detector, the Cf for the LS radon detector is 6.20 ± 0.15 (counts/h)/(Bq/m^3), derived from calibration data. The uncertainty is statistical only.

4. Sensitivity Estimation and Prospect

Background measurements for both Si-PIN and LS radon detectors were performed to estimate sensitivity. The ^{21} Po event rate from Si-PIN background data (87.4 hours) is 0.39 ± 0.067 counts/h. For the LS radon detector, the coincident signal event rate is 1.00 ± 0.13 counts/h, derived from 55.0 hours of data. Sensitivity can be estimated using Equ. 2 [13]:

$L = 1.64 \times \ BG / Cf$

where L is the sensitivity, BG is the statistical uncertainty of the background event rate, and Cf is the calibration factor. Consequently, the sensitivities are approximately 4.2 mBq/m³ and 34.4 mBq/m³ for the Si-PIN and LS radon detectors, respectively.

According to Ref. [14], when at diffusion equilibrium, radon concentrations in water and air are correlated by the Ostwald coefficient, with the ratio of radon concentrations in water to air given by Equ. 3:

$R = 0.105 + 0.405e\hat{}(-0.0502T)$

where R is the ratio and T is the temperature in °C. Thus, radon concentration in water can be derived from air measurement results.

Both the Si-PIN radon detector and the LS radon detector are currently operating successfully with the JUNO prototype, and both show potential for development into online radon concentration monitoring devices for the JUNO veto detector.

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