Study of the radon removal and detection for JUNO

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Abstract. The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose underground experiment with primary physics goal the neutrino mass hierarchy determination. For the sake of suppressing the radioactivity from the surrounding rocks and tagging the cosmic muons, the central detector is surrounded by a water Cherenkov detector. Therefore, the strict requirements are put forward for intrinsic radioactivity in water, i.e., the radon concentration should be less than 0.2 Bq/m^3. In order to monitor the radon concentration in water, a high sensitivity detector has been developed. The degassing membrane device and the micro-bubble generator were installed in the JUNO prototype water system to study the radon removal in water.

1. The JUNO experiment

Despite recent great progress in neutrino physics, the neutrino mass hierarchy (MH) and the leptonic CP-violating phase are still unknown. The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator detector of unprecedented 3% energy resolution (at 1 MeV) with multi-purpose measurements located 700 m deep underground cavern[1]. The main physics goals of JUNO is determination of MH by detecting reactor neutrinos from the Yangjiang and Taishan Nuclear Power Plants, because different neutrino mass hierarchies create different survival spectra. The JUNO experiment with a very large target mass, good energy resolution and hopefully an high radiopurity level can also have the potentiality to contribute significantly to the precision measurements of oscillation parameters, solar neutrinos and supernova neutrinos measurements and so on.

To tag cosmogenic muons and suppress fast neutrons, the outer of the central detector is filled with 35 kton ultra pure water and instrumented with 2400 MCP-PMTs as the water Cherenkov detector which also can be used as passive shielding for radioactivity from surrounding rock. Three basic requirements have been put forward for the ultra-pure water system, which are to keep the overall detector temperature at $21 \pm 1\,^{\circ}$C, keep the water clean and keep the intrinsic background low, especially the radioactive radon which is soluble in water and can be emanated from the surface of various radium containing substances, including the wall of the water pool, the PMT glass, the stainless steel, etc. Thus the water system should have the function of removing the radon in water[2].

2. Impact of radon on the MH sensitivity

A measure of the MH sensitivity ($\Delta\chi^2$) is defined as the difference of the minima obtained by fitting the neutrino spectrum assuming the normal MH or inverted MH with the χ^2 method[3].

The radioactivity of radon and its daughters in water will get into the central detector of JUNO to form the accidental background which can reduce the MH sensitivity. The impact of radon in water on the reduction of $\Delta\chi^2_{MH}$ can be calculated with the JUNO simulation software. In simulation, the projected radioactivities which include ^{238}U, ^{232}Th, ^{60}Co, ^{40}K of detector materials other than water are set by the value in the literature[3]. The Tyvek reflective film divides the pool into an inner pool which is water layer between LS and PMTs and an outer pool. Assuming the radon is uniformly distributed in the inner pool in the simulation, the relationship between the MH sensitivity and radon concentration in water is shown in Fig.1 (left), where the figure inserted at the upper right corner is an enlarged view of the low concentration area.

A fiducial volume cut is necessary to reject the external radioactivity, thus reduce the accidental background. When the effective volume is smaller, the external radioactivity is less likely to enter into the effective volume to form accidental background. The smaller the accidental background is, the greater the MH sensitivity is. However, when the effective volume is too small, the decrease of the IBD statistics will also lead to the decrease of the MH sensitivity. The relationship between the MH sensitivity and the fiducial volume cut is shown in Fig.1 (right).

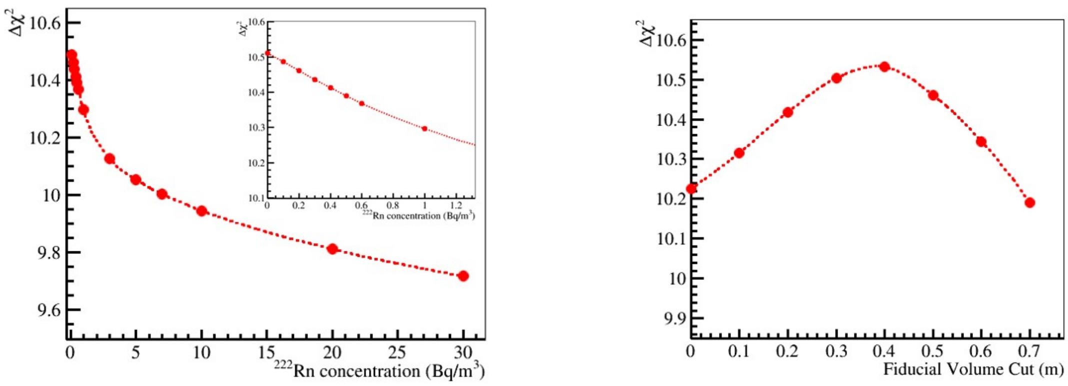

Figure 1. Left: radon concentration in water dependence of the MH sensitivity while applying an R $\leq$ 17.2 m (R: the radius of central detector) fiducial volume cut. Right: the relationship between the MH sensitivity and the fiducial volume cut when the radon concentration in water is 0.2 Bq/m^3.

For background budget, the rate of accidental background need to be controlled below 1 /day in consideration of the IBD rate about 60 /day and the reduction of $\Delta\chi^2_{MH}$ caused by radon in water need to be less than 0.1. Therefore, the radon concentration in water was proposed to be less than 0.2 Bq/m^3 for the JUNO experiment.

3. The radon measurement system

A high sensitivity radon concentration measurement system has been developed to measure the radon concentration in water and the detail information about the detector can be found in Ref.[4]. Measurement limitations suffered by predecessor detectors due to materials and detector structure used in their construction have been largely overcome in designing the new detector. Compared with the previous measurement system, the main changes are as follows:

(i) Remove the copper vessel in the radon detector and a negative high voltage is supplied to the p-layer of the photodiode using the high voltage divider instead of a positive high voltage being supplied to the copper vessel to generate the electrical field, while the stainless steel vessel is held at ground. The scheme of new detector structure scheme is shown in Fig.2 (left).

(ii) Replace the $CaSO_4$ desiccant which can emanate radon with the refrigerator which is used to keep the relative humidity lower. Because the positively charged ^{222}Rn daughter nuclei (^{214}Po and ^{218}Po) can be captured and neutralized by water in gas, the daughters collection efficiency depends on the absolute humidity. The dew-point temperature was controlled by the refrigerator in order to vary the absolute humidity throughout the entire system. The defined calibration factor (C_f) can indicate the collection efficiency of the daughters[5]. The relationship between C_f and the absolute humidity is shown in Fig.2 (right).

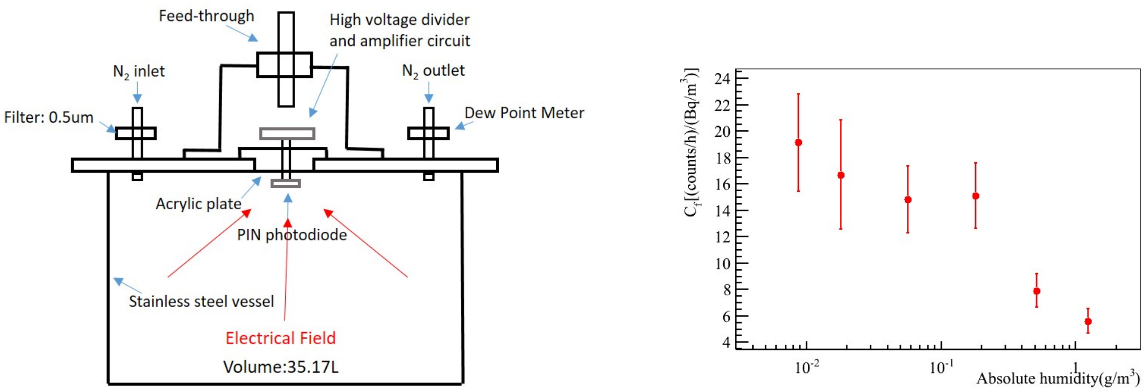

Figure 2. Left: the scheme of radon detector. Right: absolute humidity dependence of the calibration factor.

The background for measuring radon concentration in water is about 8 ± 3 mBq/m^3 obtained by circulating nitrogen gas filled in measurement system during the background experiment.

4. Radon removal and results

Condition	Concentration (mBq/m^3)	Removal efficiency
Case 1	543 ± 54	–
Case 2	34 ± 7	94%
Case 3	5 ± 3	99%

Table 1. The measurement results of radon concentration in water at different conditions.

In the previous radon removal experiments[2], the degassing membrane device[6] was used for radon removal. According to the measurement results, radon removal efficiency is correlated with gas concentration in the water and the inlet pressure of the water.

To improve the radon removal efficiency, the micro-bubbles generator which was installed in the prototype system is used to increase the nitrogen gas in the water in consideration of the self-pressurization and dissolution effect of micro-bubble. The radon removal efficiency has been tested at different conditions and the preliminary results is shown in table1. In case 1, the degassing membrane and micro-bubble generator were been bypassed, the radon concentration without radon removal is about 543 mBq/m^3. The measurement results are shown in case 2 when only degassing membrane was used to remove radon from water. Simultaneous use of degassing membrane and bubble generator can greatly increase the efficiency of removal radon in water, and the relevant results are shown in case 3. The experimental results show that the radon concentration in water after radon removal is less than 10 mBq/m^3 which can satisfy the requirement of JUNO.

5. Conclusion
The JUNO is a multi-purpose underground experiment with the neutrino mass hierarchy determination as a primary physics goal. According to the Monte Carlo simulation of JUNO experiment, the radon concentration in the water should be less than 0.2 Bq/m^3. The Liqui-Cel degassing membranes and micro-bubbles generator are used to remove the radon in water, and a high-sensitive radon detector has been developed for radon concentration measurement. After the radon removal, the radon concentration in the water can fulfill JUNO's requirements.

6. References
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