PROCEEDINGS OF SCIENCE

The radon and radium concentrations in water measurement systems for JUNO's Water Cherenkov Detector

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The Jiangmen Underground Neutrino Observatory (JUNO), a 20 kton multi-purpose low background liquid scintillator detector, was proposed primarily to determine the neutrino mass ordering. To suppress the radioactivity from the surrounding rocks and tag cosmic muons, the JUNO central detector is submerged in a water Cherenkov detector filled with 35 kton ultrapure water and equipped with 2400 20-inch microchannel plate photomultiplier tubes. Strict requirements are set for the intrinsic radioactivity of the ultrapure water, i.e., the ^{222}Rn concentration should be less than 10 mBq/m^3. As the progenitor of ^{222}Rn, the concentration of ^{226}Ra should also be precisely measured and kept well below 10 mBq/m^3. In this proceeding, the details of two measuring systems, optimized to achieve a sensitivity of $\sim$1 mBq/m^3 for the radon concentration in water and of $\sim$13 μBq/m^3 for the radium concentration in water, will be described.

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1. JUNO

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton Liquid Scintillator (LS) detector in a laboratory located 700 m underground in South China. An excellent energy resolution and a large fiducial volume offer exciting opportunities for addressing many important topics in neutrino and astroparticle physics. With six years of data, JUNO will determine the neutrino mass ordering at 3-4 σ significance as well as the neutrino oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and $|\ \Delta m^2_{32}\ |$ to the precision of 0.6% or better by detecting reactor antineutrinos from the Taishan and Yangjiang nuclear power plants. Moreover, JUNO can also observe neutrinos from other sources, including supernova burst neutrinos, diffuse supernova neutrino background, geo-neutrinos, atmospheric neutrinos, and solar neutrinos [1].

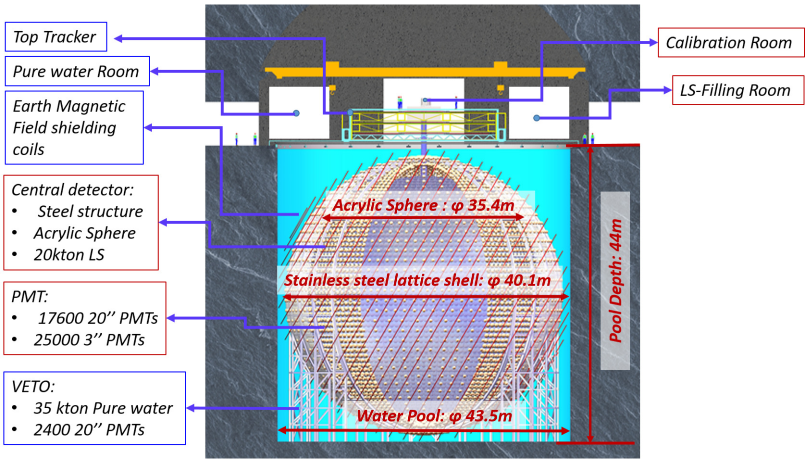

Figure 1: Scheme of the JUNO detector.

Fig. 1 shows the scheme of the JUNO detector [2]. The 20 kton Ultra-pure LS target is contained in 35.4 m diameter spherical acrylic vessel and the light emitted by LS is watched by 17612 20-inch and 25600 3-inch PhotoMultiplier Tubes (PMTs). The entire LS detector is submerged in a water Cherenkov detector (WCD). On the top of the WCD, a Top Tracker (TT), which covers ~60% of the surface, will be installed to measure the muon directions with high precision.

2. The WCD

The WCD, which consists of 35 kton of ultrapure water and 2400 20-inch MicroChannel Plate PMTs (MCP-PMTs), serves as an active veto for cosmic muons as well as a passive shield against external radio activities. The muon tagging efficiency of WCD is larger than 99% and the fast neutron background from muon spallation can be reduced to ~0.1 event/day [2]. The performance of the WCD requires stable working conditions over the future duration of the experiment.

An ultra-pure water system will be used to provide ultrapure water, monitor the purity of the water, and remove the radioactive isotopes from the water. Fig. 2 shows the schematic diagram of the water system. Furthermore, the water system also can help to keep the temperature of the acrylic sphere stabilized to 21 ± 1 °C to maintain the detector's mechanical stability. The water system includes two plants, one on the surface and one underground. The output water from the surface plant will be transported to the underground plant by stainless steel pipes. According to the background budget of the JUNO detector [2], the radon (^{222}Rn) and radium (^{226}Ra) concentrations in the ultra-pure water should be reduced to less than 10 mBq/m^3.

According to the working principle of each device in the water system, Reverse Osmosis (RO), Electrode De-Ionization (EDI), and resin play a major role in the removal of radium from the water, while micro-bubble and degasser play a major role in the removal of radon from the water.

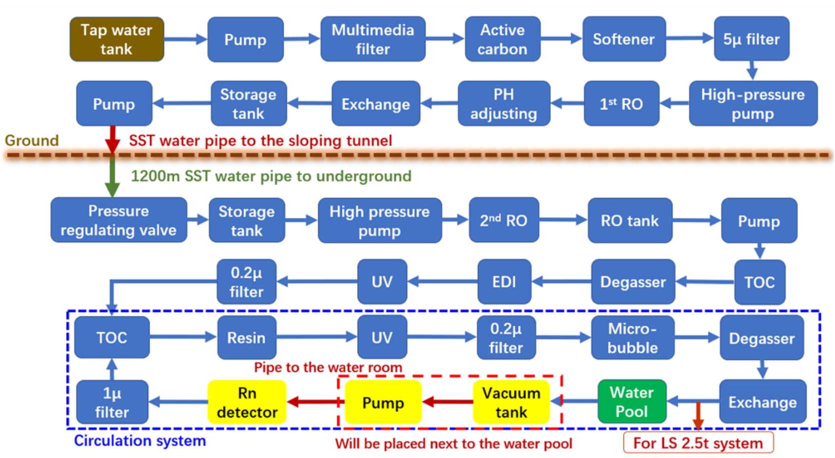

Figure 2: Schematic diagram of the ultra-pure water system.

3. The radon concentration in water measurement system

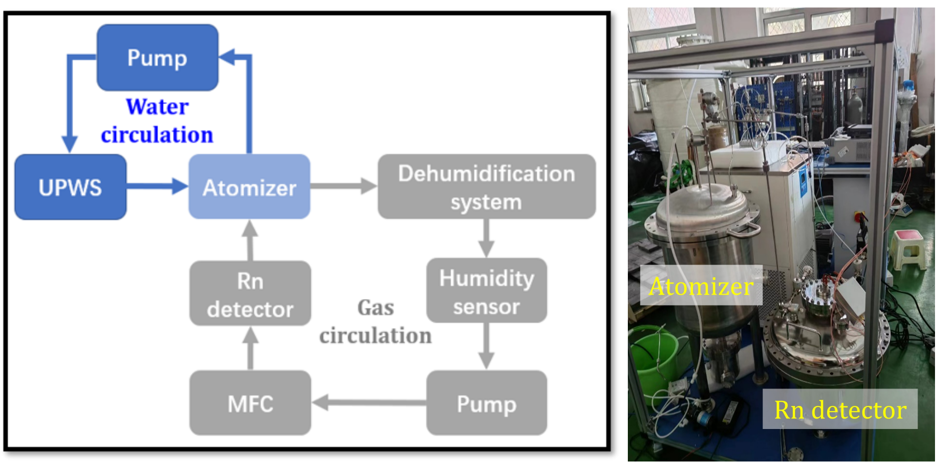

Figure 3: Left: The schematic diagram of the measurement system. The atomizer is used to transfer radon from water into gas by spraying, the dehumidification system is used to reduce the relative humidity of the gas, the pump is used for gas circulation, the MFC is used to control the gas flow rate, and the Rn detector is used to measure the Rn activity. Right: A photo of the system.

To measure the radon concentration in water, a semi-automatic measurement system based on electrostatic collection has been built. Fig. 3 shows the schematic diagram and a photo of the system. Software based on a programmable logic controller has been developed for remote operation. Radon in water can not be directly measured, it has to be transferred into gas. The atomizer facilitates the transformation of radon from water to gas through the process of spraying. When it comes to equilibrium, the radon concentration ratio in water to gas follows Eq. 1 [3]:

$$R = 0.105 + 0.405e^{-0.0502T} \tag{1}$$

where R is the ratio and T is the temperature in the unit of Celsius.

The radon detector measures the concentration of radon in the gas by detecting the α decay of ^{222}Rn daughters. The detection efficiency of the detector is correlated with the humidity of the gas, the lower the humidity the higher the detection efficiency. The dehumidification systems can reduce the relative humidity of the gas to less than 3%. The details of the detector can be found in Ref. [4]. Based on the background measurement result, the sensitivity of the system is ~1 mBq/m^3.

4. The radium concentration in water measurement system

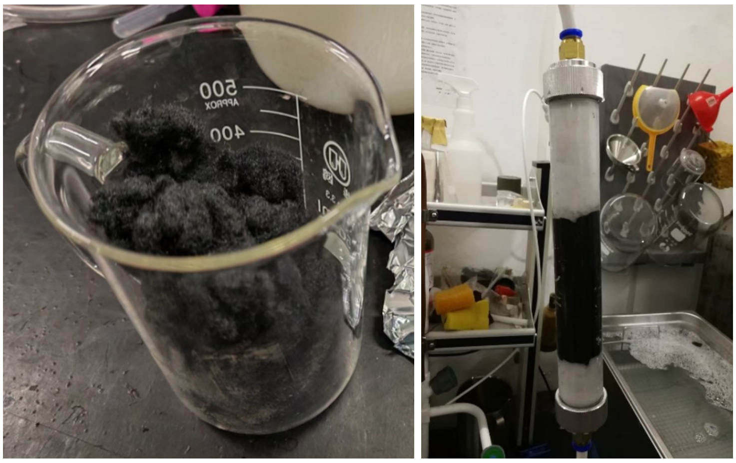

Figure 4: Left: A picture of the Mn-fiber. Right: A picture of the radium extraction column.

The radium concentration in water measurement system consists of a radium extraction column and a set of radon emanation measurement system. The main part of the extraction column is the Mn-fiber located in the center of the column, which can adsorb the dissolved radium ions from the flowing water. The Mn-fiber is MnO_2 attached polyethylene fiber. The radium extraction efficiency of Mn-fiber is calibrated with a ^{226}Ra solution. According to the calibration result, 5 g Mn-fiber can extract radium from 10 m^3 water with an efficiency of ~88%. Fig. 4 shows pictures of Mn-fiber and the extraction column.

The ^{226}Ra activity is determined by its gaseous daughter ^{222}Rn using a radon emanation system with a sensitivity of 73 μBq/sample. Fig. 5 shows a picture of the radon emanation system, which consists of a Mn-fiber container, a set of dehumidification devices, a Mass Flow Controller (MFC, 1179A MKS), a vacuum pump (ACP40, Pfeiffer), and a radon detector. The Mn-fibers are sealed in the container for several days before the measurement, allowing the ^{226}Ra present on them to decay and produce ^{222}Rn. The ^{222}Rn gas is purged from the container to the radon detector by

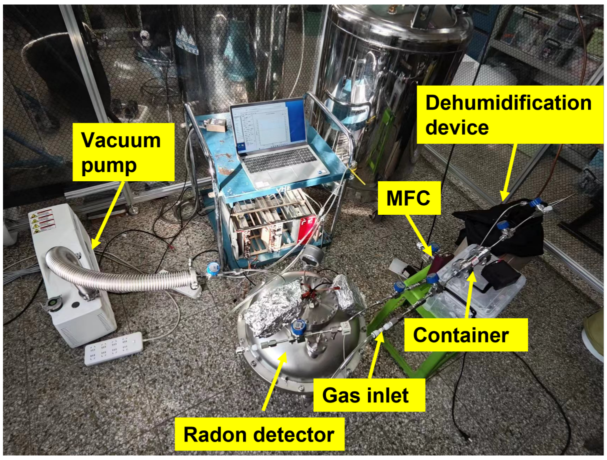

Figure 5: A picture of the radon emanation measurement system. The container is used for Mn-fiber sealing. The functions of the MFC, the dehumidification device, and the radon detector are similar to the ones shown in Fig. 3. The vacuum pump is used to vacuum the radon detector before gas transfer.

evaporating nitrogen. Based on the background measurement and radium extraction calibration results, the sensitivity of the system is ~13 μBq/m^3.

5. Conclusion

JUNO is a multi-purpose neutrino experiment and its main physics goal is to determine the neutrino mass ordering. To suppress the background from the cosmic muons as well as from the external radioactivities, the central detector is submerged in a water Cherenkov detector. To reduce the accidental background in the central detector, the ^{222}Rn and ^{226}Ra concentrations in the water should be reduced to less than 10 mBq/m^3. Two setups for measuring ^{222}Rn (^{226}Ra) concentration in water with a sensitivity of ~1 mBq/m^3 (13 μBq/m^3) have been developed and the installation status presented.

6. Acknowledgement

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