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The radon monitoring system in Daya Bay Reactor Neutrino Experiment

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ABSTRACT

We developed a highly sensitive, reliable and portable automatic system (H^3) to monitor the radon concentration of the underground experimental halls of the Daya Bay Reactor Neutrino Experiment. H^3 is able to measure radon concentration with a statistical error less than 10% in a 1-h measurement of dehumidified air (R.H. 5% at 25 °C) with radon concentration as low as 50 Bq/m^3. This is achieved by using a large radon progeny collection chamber, semiconductor α-particle detector with high energy resolution, improved electronics and software. The integrated radon monitoring system is highly customizable to operate in different run modes at scheduled times and can be controlled remotely to sample radon in ambient air or in water from the water pools where the antineutrino detectors are being housed. The radon monitoring system has been running in the three experimental halls of the Daya Bay Reactor Neutrino Experiment since November 2013.

1. Introduction

The main goal of the Daya Bay Reactor Neutrino Experiment is to determine the neutrino mixing angle θ_{13}. Eight anti-neutrino detector modules (ADs) are installed in three underground experimental halls. In order to suppress backgrounds related to cosmic-ray muons and natural radioactivity, the ADs are immersed in water pools [1].

In an underground environment like this, radioactive radon gas can be easily found in air. Isotopes of thorium and uranium (^{232}Th, ^{235}U and ^{238}U) in rocks produce gaseous ^{220}Rn, ^{219}Rn and ^{222}Rn respectively in their decay chains. ^{219}Rn in air has negligible impact to the experiment since its half-life is only 3.96 s. ^{220}Rn has a half-life of 55.6 s, so it can exist for a longer time in air and may accumulate to a measurable quantity. For ^{222}Rn, it has a half-life of 3.83 days. Numerous α-particles are generated from ^{222}Rn and its progenies along the chain: ${}^{222}_{86}\mathrm{Rn} \xrightarrow[3.83\ \mathrm{d}]{5.40\ \mathrm{MeV}\ \alpha} {}^{218}_{84}\mathrm{Po} \xrightarrow[3.05\ \mathrm{m}]{6.00\ \mathrm{MeV}\ \alpha} {}^{214}_{82}\mathrm{Pb} \xrightarrow[26.8\ \mathrm{m}]{\beta^-} {}^{214}_{83}\mathrm{Bi} \xrightarrow[19.7\ \mathrm{m}]{\beta^-} {}^{214}_{84}\mathrm{Po} \xrightarrow[164\ \mu\mathrm{s}]{7.69\ \mathrm{MeV}\ \alpha} {}^{210}_{82}\mathrm{Pb} \xrightarrow[22.3\ \mathrm{y}]{\beta^-} {}^{210}_{83}\mathrm{Bi} \xrightarrow[5.01\mathrm{d}]{\beta^-} {}^{210}_{84}\mathrm{Po} \xrightarrow[138\mathrm{d}]{5.30\ \mathrm{MeV}\ \alpha} {}^{206}_{82}\mathrm{Pb}$. These α-particles can induce background in the experiment. Furthermore, due to its relatively long half-life, ^{222}Rn can accumulate to a high concentration in poorly ventilated space and pose a health hazard. In view of its importance, the term "radon" is used to refer specifically to ^{222}Rn in this paper unless otherwise stated.

Radon in air is particularly difficult to handle amongst common natural radioactive backgrounds. It can diffuse into the ADs through any unnoticeable leak or radon-permeable materials, and then dissolve in the liquid scintillator. The dissolved radon and its progenies can cause correlated background (from α decays) and singles background (from β decays) mimicking antineutrino signals. To reduce the amount of radon in the vicinity of the ADs, dry nitrogen gas is used to flush out air in the space between the water pool cover and the pool water, and in the dry ducts connected to the ADs. The pool water is also purified and recirculated. In addition to suppressing radon in the experiment, there is a need to monitor continuously its concentration, especially in the air in the experimental halls, and in the water surrounding the ADs.

A preliminary survey of airborne radon was carried out with an AB-5 detector (Pylon Electronics Inc.) [2] in the experimental halls (EH1, EH2, and EH3) of Daya Bay. Radon concentrations from about 50 Bq/m^3 to a few hundreds of Bq/m^3 were recorded at various locations. We require the statistical error of a meaningful monitoring of the radon concentration to be less than 10% for 1-h sampling of air with radon concentration down to 50 Bq/m^3. It is convenient to express this requirement by a detector calibration

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factor (C.F.) of 30 Bq/m^3/cpm with the definition:

$$\text{C.F.} = \frac{\text{radon concentration [Bq/m}^3]}{\text{number of counts per minute [cpm]}}. \quad (1)$$

Also, the detector should be sensitive to a low radon concentration of 0.5 Bq/m^3 and portable, for carrying out *ad hoc* radon measurements (e.g. radon in gas flushing the ADs).

The monitoring system should operate as an integrated system. It has to control the measurements of radon in air and water automatically following a customizable schedule. The radon data and the measurement conditions should be ready to be processed and uploaded to a centralized system of the experiment.

Thus a highly sensitive radon monitoring system was developed to meet these requirements. Details of this system are introduced in this paper. In Section 3, the design and construction of the system are presented. Calibration and optimization of the radon detector are described in Section 4. In Section 5, the performance of the system in the underground halls is discussed.

2. Other radon monitoring equipment

Many commercial radon detectors employ Lucas cell or electrostatic method for radon progenies counting. Lucas cell-based detectors like AB-5 are renowned for their stability and simplicity of operation. However, the cell does not distinguish the α-particles generated from radon, ^{218}Po and ^{214}Po. As the two nuclides preceding ^{214}Po have half-lives of about 20 min, it takes about 3 h for radon and ^{214}Po to reach equilibrium inside the Lucas cell. This type of detector is not designed for monitoring the hourly fluctuation of radon continuously.

Detectors employing electrostatic method to collect radon progenies can have a quicker response. Many of them are able to take an energy spectrum of α-particles, enabling the selection of the fast-response ^{218}Po events for counting. RAD7 (Durridge Company Inc.) [3] is a typical and popular model of this type of detector. However, due to the small volume of its internal sample cell (0.7 L), RAD7 has a C.F. of only 148 Bq/m^3/cpm. Another detector of this type is ERS-2-S (Tracerlab GmbH) [4], which has a higher sensitivity. However, the α-particle energy spectrum has limited resolution for easy background identification.

Excellent sensitivity reaching 1 mBq/m^3 or better can be achieved by radon extraction facilities built for some underground experiments [5–7]. These facilities utilize collection chamber of hundreds of liters in volume. They take up large spaces and are not intended to be portable.

3. Radon monitoring in the Daya Bay Experiment

In order to meet the requirements stated in Section 1, the Hong Kong High-sensitivity High-reliability detector (H^3) is designed to have a C.F. better than 30 Bq/m^3/cpm with superb portability. The whole system is integrated to the hardware and software of the Daya Bay Experiment in a simple manner. It is capable to control radon measurements in air and water samples, and present the real-time results through network.

As depicted in Fig. 1, the system is installed in the electronics room of each experimental hall. There are two types of run mode: "air run" for measuring the radon concentration of the air sample extracted from the hall; and "water run" for measuring the radon concentration of the water sample obtained from the recirculation system of the water pool. The samples are not required to flow at high speed or be pressurized. The sampling points can be set up easily by plugging the tubings into the push-in fittings.

The H^3 is designed to measure airborne radon directly. For radon dissolved in water sample, the gas is allowed to diffuse from water to air in a degassing unit first. Then the air is pumped to the H^3 for measurement.

A software interface is written in LabVIEW Virtual Instrument (VI) [8] to control and monitor the operation of the radon monitoring system. The host computer (host PC) of the LabVIEW VI is connected to a set of control valves and flow sensors installed along the sample pathways through a USB data acquisition module. The VI also reads the H^3 data via a RS-232 port. Then it processes the data with the calibration constants set by the system administrator. A copy of the processed data is also sent to the remote Detector Control System (DCS) of the experiment which centralizes all the environmental data and detector operation conditions.

3.1. H^3 detector

The H^3 detector is made of a rack-mount VME-4U chassis (178 mm (*H*) × 482 mm (*W*) × 279 mm (*L*)) that houses a radon progeny collection chamber, an α-particle detector, a high-voltage generator, and front-end electronics, weighing less than 5 kg in total.

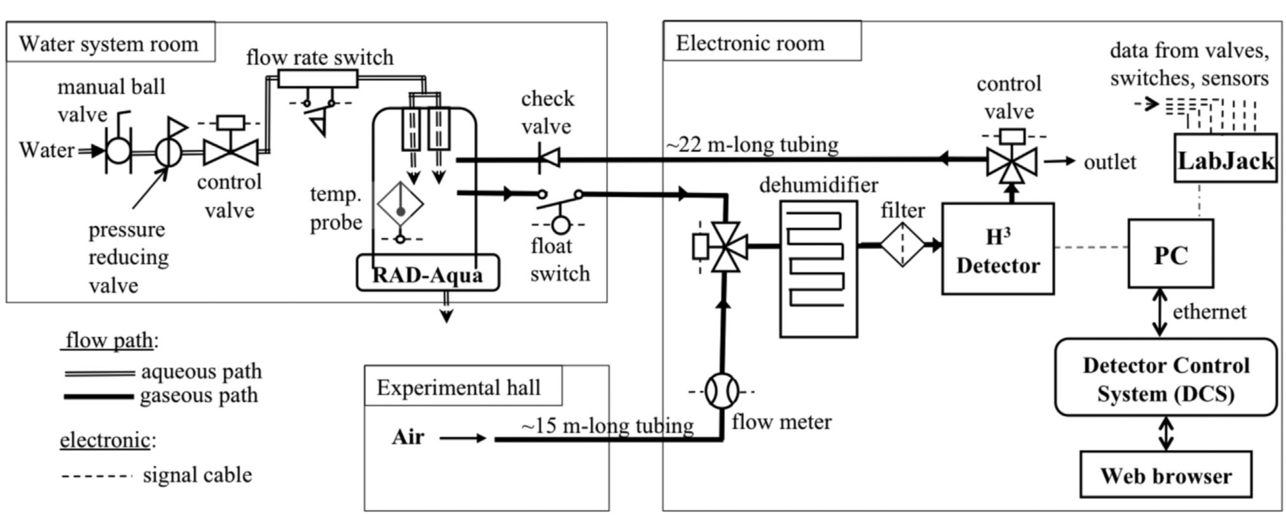

Fig. 1. Schematic diagram of the radon monitoring system in each Daya Bay experimental hall. Details of components can be found in Sections 4 and 5.