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Single channel beta–gamma coincidence system for radioxenon measurement using well-type HPGe and plastic scintillator detectors

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ABSTRACT

In order to improve detection sensitivity for radioxenon isotopes, a new single channel beta–gamma coincidence system has been developed. The system combines a well-type High-purity Germanium (HPGe) detector to measure gamma or X radiation and a plastic scintillator detector to obtain electron radiation. A ^{133}Xe sample has been produced and the radioactive concentration was determined with length-compensated method based on three internal gas proportional counters. The performance of system has been checked by measuring ^{133}Xe sample with and without coincidence. The coincidence detection efficiency of 81 keV gamma-ray from decay of ^{133}Xe was calibrated to be 0.34 ($1 \pm 2.4\%$), and the Minimum detectable activity (MDA) of the beta–gamma coincidence system for ^{133}Xe was determined to be 1.8 mBq after one day of measurement.

1. Introduction

The radioxenon measurement in samples of atmospheric air gases is very important for verification system of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) [1–3]. Since four of the radioxenon isotopes, namely ^{133}Xe, ^{135}Xe, ^{133m}Xe and ^{131m}Xe, have relative large fission yields and half-lives long enough to offer realistic detection probabilities on continental or even global distances, they are paid particular attention. Detection of four radioxenon isotopes is typically based on either beta–gamma coincidence spectroscopy system using scintillator detector or high resolution gamma-ray spectroscopy system with HPGe detector. Four countries have provided measurement system for radioxenon measurement [4]: the USA made a system called ARSA, Russia constructed ARIX, Sweden built SAUNA and France offered the SPALAX system. Three of the systems, the ARSA, the ARIX and the SAUNA, use very similar measurement techniques and produce two-dimensional beta–gamma coincidence spectra [5–7]. The SPALAX system is based on high-resolution gamma spectroscopy [8] with HPGe detector. In the three beta–gamma coincidence spectroscopy system, electron radiation is detected with plastic scintillator detector, and gamma or X radiation is detected by NaI detector. The beta–gamma coincidence technique has higher detection sensitivity than gamma-ray spectroscopy with single HPGe detector. But, the poor energy resolution of NaI detector for gamma and X radiation limits the improvement of detection sensitivity. Muons and their secondary particles can coincidently trigger beta and gamma detector pulses, so muon-gamma anticoincidence should reduce photon background originated from muons and their secondary particles. In 2010, Schroettner et al. [9] developed a high-resolution beta–gamma coincidence, muon-gamma anticoincidence system for radioxenon measurement. The measurement system combined a planar HPGe detector, a Silicon Surface Barrier (SSB) detector to obtain high-energy resolution for gamma and electron radiation, and six plastic scintillation detectors for cosmic muon. The application of muon-gamma anticoincidence further reduced the background by a factor of about two. The Minimum Detectable Activity (MDA) of the system [9] for ^{133}Xe during 7 days measuring time is 1.4 mBq. Although the energy resolution of planar HPGe detector [9] is better than NaI, the photo peak efficiency for radioxenon detection was less than NaI, which limits improvement of detection sensitivity. And, the system is more complicated than the above described system.

The beta–gamma coincidence spectroscopy system, developed under this study, combined a well-type HPGe detector to measure gamma or X radiation, and a plastic scintillator detector to measure electron radiation. The gamma and X-rays from radioxenon isotopes were detected by well-type HPGe detector with high-energy resolution and high-detection efficiency, so the system may be a new and successful approach for improved radioxenon measurement. After the system was set up, the performance was checked by ^{133}Xe sample.

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2. Experiments and methods

2.1. Beta–gamma coincidence measurement system

In order to improve energy resolution and detection efficiency of gamma and X rays from decay of radioxenon, we used a well-type HPGe detector from ORTEC with FWHM of 2.0 keV at 1332 keV of ^{60}Co. The detector has a crystal height of 65.8mm and diameter of 60.8mm, and a well depth and diameter of 40 and 16 mm, respectively. The crystal is mounted in an aluminum end cap of 0.5 mm thickness.

The cylindrical beta detector cell fabricated from ST401 plastic scintillator material was designed for detection of the electrons from beta decay or internal conversion from decay of radioxenon. The main characteristics of ST401 scintillator were equivalent to the NE102 scintillator. Inner volume of beta detector cell was 6.34 cm^3, with an inner diameter of about 12.8 mm, and a length of about 56 mm. The thickness of the scintillator was 1.5 mm. The gaseous sample was injected into beta detector through a 1/16 in. stainless steel pipe, inserted and glued onto the cylinder.

After the beta detector was placed in the well of HPGe detector, a simultaneous measurement of both the beta- and gamma-ray energies would most likely improve the possibility of detecting radioxenon in a given sample.

The measurement system was shielded with shielding house. The house was made of 100-mm-thick bricks of low-activity lead. In addition, a 1-mm thick cadmium, copper and aluminum layer was placed inside the lead shielding to remove the X-rays induced in the lead by ambient gamma-ray radiation. The house was 1 m long, 1 m wide and 1.8 m high.

A schematic drawing and a photo of the detector system can be found in Fig. 1.

The signal of the HPGe detector was input into the digital multichannel spectrum (ORTEC Dspec-plus) for gamma and X-ray energy spectrum measurement. Standard NIM electronics were used to process the beta detector signals. After preamplification by photo multiplier tube (PMT), the signal of the beta detector was input into amplifier (ORTEC 475) and digitized by a timing discriminator (ORTEC 551). After that, the signal was delayed by gate and delay generator (ORTEC416A), and was used to gate the Dspec-plus which digitizes the pulse heights from HPGe detector. When the delay time of ORTEC 416A was adjusted to be 12.5 μs, the signal of both the beta- and gamma-ray was simultaneously detected and beta–gamma coincidence spectrum was formed. The Windows-based software, GammaVision from ORTEC, was used for obtaining and analyzing the energy spectrum. In order to eliminate electronic noise in the low energy region of beta detector, the discriminator threshold for the beta detector was adjusted to 10 keV. Fig. 2 showed a schematic drawing of the electronics for data acquisition.

2.2. Calibration and MDA

Energy calibration of the HPGe detector was performed from 25 keV to 500 keV using selected gamma- and X-ray lines from three radioactive point sources (^{133}Ba、 ^{57}Co and ^{241}Am). As a result, FWHM of 81 keV for ^{133}Xe was calibrated to be 1.1 keV.

The beta efficiency was retrieved by comparing HPGe spectra recorded with and without coincidence. The gamma-ray photo peak efficiency for ^{133}Xe was determined using ^{133}Xe gaseous source whose radioactive concentration had been determined.

The radioactive concentration of ^{133}Xe was obtained with length-compensated method mentioned in Refs. [10] and [11]. Here we provide a summary of the measurement procedure.

Enriched U_3O_8 (90% ^{235}U) sealed in a quartz capsule with a volume of 1 cm^3 was irradiated for 1 h at the core of a reactor where the thermal neutron flux was approximately 10^{13} n cm^{-2} s^{-1} and fission product gases were produced. After 7 days of cooling, in which the krypton and other xenon isotopes have shorter half lives and do not interfere with the ^{133}Xe of interest, the quartz tube was crushed in the source preparation equipment presented in Fig. 3, and then gaseous ^{133}Xe sample was imported in the mixing chamber and mixed with a counting gas (P10:90%Ar_2 + 10%CH_4). Finally, the homogenized gases were charged simultaneously into the three internal gas proportional counters (L counter, M counter and S counter presented in Fig. 3) and the beta detector cell.

The radioactive concentration of ^{133}Xe was obtained with length-compensated method based on three internal gas proportional counters. The three copper gas counters with volumes of 267.1, 178.1, and 89.2 cm^3, respectively, have an identical end

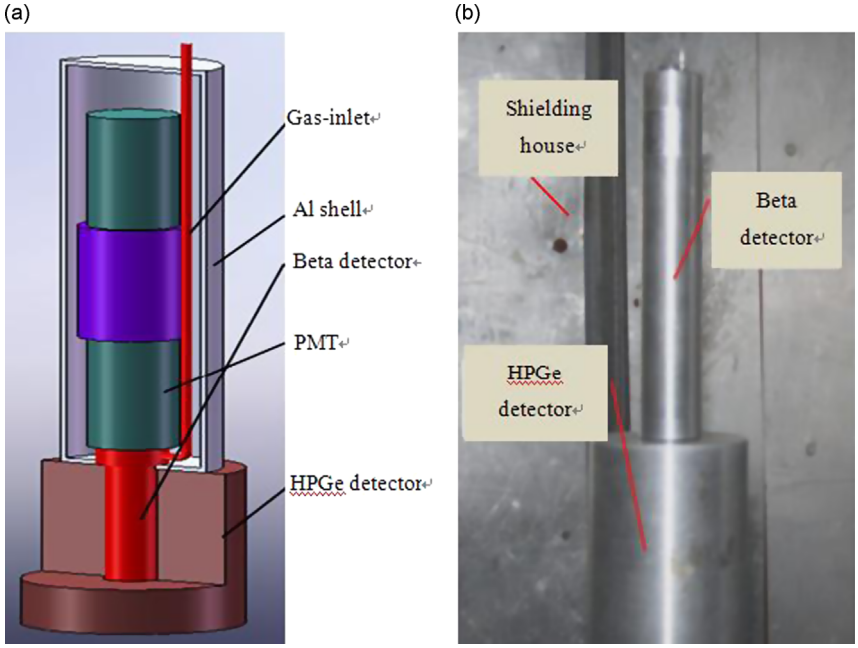

Fig. 1. (a) A schematic drawing of the detectors system, and (b) a photo of the detectors system.