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Simulation and experimental measurement of radon activity using a multichannel silicon-based radiation detector

F.B. Ozdemir[a], A.B. Selcuk[b], S. Ozkorucuklu[c], A.B. Alpat[d], T. Ozdemir[e,*], N. Özek[f]

[a] *Beykent University, Istanbul, Turkey*
[b] *İzmir Demokrasi University, İzmir, Turkey*
[c] *Istanbul University, Istanbul, Turkey*
[d] *Sabanci University, Turkey*
[e] *Bartin University, Bartin, Turkey*
[f] *Süleyman Demirel University, Isparta, Turkey*

HIGHLIGHTS

- A new -generation semiconductor micro-strip detector was used for detecting radon (Rn-222) activity.
- Count-ADC channel, eta-charge, and dose–response graphs were experimentally obtained.
- The radon simulation in radiation detector was theoretically performed using the Geant4 software package.
- Radioactive decay, energy generation, energy values, and efficiency values were plotted using the root program.

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ABSTRACT

In this study, high-precision radiation detector (HIPRAD), a new-generation semiconductor microstrip detector, was used for detecting radon (Rn-222) activity. The aim of this study was to detect radon (Rn-222) activity experimentally by measuring the energy of particles in this detector. Count-ADC channel, eta-charge, and dose–response values were experimentally obtained using HIPRAD. The radon simulation in the radiation detector was theoretically performed using the Geant4 software package. The obtained radioactive decay, energy generation, energy values, and efficiency values of the simulation were plotted using the root program. The new-generation radiation detector proved to have 95% reliability according to the obtained dose–response graphs. The experimental and simulation results were found to be compatible with each other and with the radon decays and literature studies.

1. Introduction

Ionization-based detection of radiation involves the measurement of radiation intensity and activity. There are numerous applications in the fields of industry and health in which ionizing radiation is used. Therefore, studies related to the improvement of radiation detectors hold great importance in these fields.

Neutral atoms or molecules acquire positive or negative electrical charge by ionizing radiation. Alpha, beta, and gamma rays; X-rays; and neutron rays are among the most commonly known types of ionizing radiation. As a form of energy, radiation can be stored in a suitable medium, partly or as a whole, and it is capable of producing an effect (Flakus, 2016).

Barnett et al. (1996) described the interaction of particles with matter, the result of such interaction, related calculations, and the Bethe-Bloch formula. Ionization-based mean energy loss is given by the Bethe-Bloch formula (Barnett et al., 1996; Leo, 1992). The basic principle of interaction in matter depends on the type of incident radiation and the particles' energy (Tsoulfanidis, 1995; Leroy and Rancoita, 2009).

Semiconductors and *PN* diodes comprise the basis of all radiation detectors. Semiconductor devices are characterized by basic physical processes and equations including the equilibrium concentration of electron–hole pairs, mobility, bias voltage, and charge density (Sze, 1981; Mishra and Singh, 2008).

The counting efficiency in the radioactivity measurement may

* Corresponding author.
E-mail addresses: firdevsbanuozdemir@beykent.edu.tr (F.B. Ozdemir), birkan.selcuk@idu.edu.tr (A.B. Selcuk), suat.ozkorucuklu@istanbul.edu.tr (S. Ozkorucuklu), balpat@sabanciuniv.edu (A.B. Alpat), tozdemir@bartin.edu.tr (T. Ozdemir), nuriozek@sdu.edu.tr (N. Özek).

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Table 1
Rn-222 decay products from U-238 chain (Alpat et al., 2007; Lbnl Web page: 〈http://ie.lbl.gov/toi/radSearch.aspS〉).

Radioisotope	Half-life	α	β	γ
^{222}Rn	3.823 days	5490 keV		510 keV
^{218}Po	3.11 min	6003 keV		
^{214}Pb	26.8 min		7300 keV	
^{214}Bi	19.9 min		1510 keV	610 keV
^{214}Po	164.3 µs	7687 keV		800 keV
$^{21\circ}$Pb	21.8 years		200 keV	46 keV
$^{21\circ}$Bi	5.01 days		1160 keV	
^{210}Po	138.4 days	5297 keV		
^{206}Pb	Stable			

depend on several factors including composition, geometry, activity, density, placement, radiation type, radiation energy, and other instrument-specific factors. Calculation of estimated efficiency can be explicitly performed as a function of these variables (MARLAP, 2014).

In principle, radiation detectors produce an output signal through interaction within the active volume of the detector. This interaction occurs as ionization and excitation of charged radiation particles such as alpha and beta particles. In the detector, the incident charged particles such as electrons and protons interact with the detector material, thereby producing electron–hole pairs along their trajectories. The count information of charged particles is processed by signal processing electronics upon collection. The detection efficiency of gamma rays and neutrons is generally lower than that of charged particles (Byun, 2016).

Radon and its decay products account for almost 55% of the current radiation dose in the USA (Miller, 2000). Radon (Rn-222) is a radioactive decay product of uranium and thoron series, and monitoring of radon is required in risk areas because of its carcinogenic nature (UNSCEAR, 2008). Radon (Rn-222) is a radioactive decay product of the U-238 chain (Table 1).

Radon, which is one of the naturally occurring radioactive inert gases in the U-238 series, is a product of α radiation of Ra-226 and has a radioactive half-life of 3.84 days. Thoron (Rn-220) and actinon (Rn-219) are the known isotopes of this colorless, tasteless, and odorless gas and have significantly shorter half-lives of 55 and 3.9 s, respectively. Accordingly, radon element is dominated by Rn-222 (UNSCEAR, 1988).

Rn-222 and Ra-226 are among the most common radionucleotides that pose serious health risks for humans. These radioactive elements with high radiation levels threaten human health by inflicting damage in lungs and other organs, upon inhalation through the respiratory tract (Marques et al., 2004). Because of its low affinity, radon does not chemically bond with tissues when inhaled, and its solubility in the tissues is very low. However, radon decay products are retained in dust and other particles, thereby producing inhalable radioactive aerosols. When inhaled, radon gas takes the particle form, which can be retained in lungs. Thus, it is taken into the body through the respiratory tract and emits radiation in every stage of the decay process until it becomes stable. The energy released as a decay product of these particles, thus, increases the risk of cancer with time (Axelson, 1995; Field et al., 2000; UNSCEAR, 2000; Lazar et al., 2003).

Tanaka et al. investigated the number of counts needed to measure radon concentration using the AlphaGUARD (a low-effective volume detector) and compared the values with those of more sensitive radiation detectors (Tanaka et al., 2017). Sharma et al. measured and evaluated mean radon concentration in water samples which ranged between 1.4 ± 0.3 and 13.3 ± 4.1 Bq 1^{-1} (Sharma et al., 2017). Testing and calibration results for a gamma-spectrometric complex based on xenon gamma-ray detector were described by Novikov et al. (2017).

Dalla Betta et al. designed and realized a radon sensor using a bipolar junction transistor (BJT), fabricated on a high-resistivity silicon substrate. The functional testing of the proposed system was provided elsewhere (Dalla Betta et al., 2013).

Silicon PIN diode-based electron-gamma coincidence detector system for noble gas monitoring, expected sensitivity, and improvements of the detector system were presented by Khrustaleva et al. (2017).

Geant4 is a toolkit used for the simulation of particle passage through matter. Its functionalities include tracking, geometry, physics models, and number of hits for use in a vast number of experiments and applications including high-energy physics, medical physics, astrophysics, space science, and radiation protection (Agostinelli et al., 2003; Allison et al., 2006).

Radiation is measured following the interaction of particles with matter. The interaction mechanism that depends on the particle's type, energy (E) , number of protons (p) in the medium of the incident particles, and atom density (ρ) is essential for understanding the physical processes. Numerous physical models have been used to initiate and analyze the interaction of particles with matter in a wide energy range (250 eV to 100 TeV). These physical models are electron, positron, photon, charged hadron, and ion interactions; electromagnetic processes; hadron physics involving muon and gamma core interactions; and subatomic decay.

In the simulation study, the efficiencies of thin and thick detectors, that were calculated separately, were named "efficiency," and the efficiency of both detectors was named the "total efficiency."

HIPRAD detector, introduced in the present study, can separate α, β, and γ particles, and anticoincidence system can prevent the effects of cosmic rays. In this experiment, the Ra-226 isotope was used as the source. Our goal in this study was to measure the Rn-222 activity obtained from the Ra-226 source, whose activity is presented in Table 1. An application of this detector is a prototype of radiation measurement system. The aim of this study was to experimentally detect radon (Rn-222) activity in HIPRAD detector that measures the energy of particles. This study summarizes the energies of alpha, beta, and gamma particles; charge distributions; eta-charge distributions; dose–response values measured in the inner and outer sides of strips; background; and efficiency of radiation detector as shown in the graphical results. Simultaneous alpha and beta measurement capability of the silicon radiation detector was verified with the experimental and simulation results. The experimental spectra of Rn-222 source were theoretically compared with the simulation results on Geant4 and root programs.

2. Materials and methods

Several types of detectors are available for radiation detection. These include gas-filled detectors, scintillation detectors, and semiconductor detectors. Silicon radiation detector is a semiconductor double-sided multichannel (strip) radiation measurement detector. Silicon detectors are used in several applications including accelerator systems, dosimeters, nuclear- and high-energy physics experiments, in the field of medical imaging, and in the determination and diagnosis of charged particles. High-precision multisilicon radiation detectors are used to measure the charge, energy, and observation times of alpha, beta, and gamma radiations in solid, liquid, and gas samples. Radiation detectors also measure the dose and activity with high precision. Several studies on the properties of silicon sensors and the performance of detector systems are available in the literature (Leo, 1992; Sze, 1981; Lutz, 1999; .Spieler, 2005).

The multichannel silicon detector (HIPRAD) is shown in Fig. 1. The radiation detector system is equipped with an anticoincidence system, pneumatic system, rechargeable battery-based power supply system, and wireless data transfer system. The anticoincidence system consists of plastic scintillators to eliminate the background radiation induced by cosmic rays (TAEK Turkish Atomic Energy Authority SANAEM Sarayköy Nuclear Research and Training Center, 2012; MAPRad, 2010).

The silicon radiation system consists of a double-sided silicon strip detector. The thin detector in HIPRAD has the dimensions of 7 cm ×