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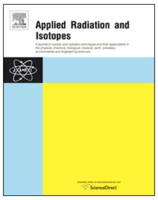

Calibration of low-level beta-gamma coincidence detector systems for xenon isotope detection

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HIGHLIGHTS

- Calibration procedure for beta-gamma coincidence detector systems described.
- Designs of various beta-gamma detectors discussed and compared.
- Uncertainty budget for the calibration procedure compiled.
- Calibration validation procedure discussed.
- Necessary work identified to resolve existing issues.

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ABSTRACT

The beta-gamma coincidence detector systems used for the measurement of the CTBT-relevant xenon isotopes (Xe-131m, Xe-133m, Xe-133 and Xe-135) in the International Monitoring System network and in the On-Site Inspection are reviewed. These detectors typically consist of a well-type or bore-through NaI crystal into which a measurement cell, serving also as a sample container, is inserted. This work describes the current calibration procedure for energy, resolution and efficiency, implementation challenges, availability and uncertainties of the specific nuclear decay data and the path forward to full calibration validation using GEANT4.

1. Introduction

Radioxenon isotopes Xe-133, Xe-135, Xe-133m and Xe-131m are identified as the tell-tale sign, i.e. the smoking gun, of a clandestine nuclear explosion and are on the list of relevant nuclides for the Comprehensive Nuclear Test Ban Treaty (CTBT) due to their relative abundance among the fission products of uranium or plutonium isotopes used for nuclear weapons, their half-lives and the fact that they can, owing to the chemical inertness of xenon gas, escape even from a well contained underground nuclear explosion (UNE) (Carrigan et al., 1996) (see Table 1 for a summary of key decay properties). The International Monitoring System (IMS) established for the verification of the CTBT has 40 stations with Noble Gas (NG), i.e. radioactive xenon, monitoring capability. Similar NG systems are also used for the On-Site Inspection (OSI) regime. A majority of these systems utilise beta-gamma coincidence detection systems [SAUNA - Ringbom et al. (1998, 2003), ARIX - Popov et al. (2005)].

Calibration of a beta-gamma detector system is a complex multistep process which includes a number of measurements involving point sources, gas sources and Monte Carlo simulations. Adding to complexity of calibrations are the interference factors from a possible radon contamination, gas matrix self-absorption as well as the interferences between different xenon isotopes which have similar decay signatures. This work describes the current calibration procedure, challenges of the method implementation, availability and the uncertainties of the nuclear decay data for the isotopes of interest and the path forward in the validation of the algorithm using GEANT4 models of the detectors.

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Table 1
Decay properties of xenon isotopes of interest.[a]

Isotope[b]	Half-life	X-ray (keV)	*I* (%)	Gamma (keV)	*I* (%)	CE (keV)	*I* (%)	Beta average/end point (keV)
Xe-133	5.2474 (5) D	30.9	47.63(7)	80.9979(11)	37.0(3)	45.0133(11)	52.9(9)	100.6(8)/346.4(24)
Xe-133m	2.198 (13) D	30.46	56.34(75)	233.219(15)	10.16(13)	198.655(15)	63.5(12)	–
Xe-131m	11.962(20) D	30.38	54.47(84)	163.930(8)	1.942(26)	129.366(8)	61.4(1.3)	–
Xe-135	9.14(2) H	32.18	5.94(15)	249.794(15)	90(3)	213.81	5.6(4)	249.793(12)/910(10)

[a] The number in parentheses is the numerical value of (the combined standard uncertainty) u_c referred to the corresponding last digits of the quoted result (GUM 1995).
[b] All data is from DDEP (www.nucleide.org) except for Xe-135, which comes from ENSDF (http://www.nndc.bnl.gov/ensdf/)

2. Materials and methods

2.1. General overview

In general, all NG monitoring systems comprise four main parts:

1) the sample input, i.e. sampling onto traps followed by gas processing using a type of preparative gas chromatography in order to extract stable xenon from atmospheric or subsoil air, while releasing all other gases,
2) quantification of the sample after finished processing, in some systems both before and after the nuclear decay measurements,
3) the final purified NG sample (with a carrier gas – helium or nitrogen) is transferred from the processing part of the system into a measurement cell. For Xenon systems the sample volume is typically 1.2–7 mL and the measurement cell is located inside the spectrometry system,
4) after the measurement, the sample is transferred to an archive container, in case re-measurements are required.

2.2. The SAUNA detector system

The SAUNA system is equipped with two (IMS) or four (OSI) detectors (Fig. 1). The SAUNA detector is an aluminium-encased vertical cylinder 4 inches in diameter and 4 inches high made of a NaI(Tl) scintillator produced by Saint-Gobain. The detector is read out by a single PMT. Approximately at the middle, the crystal has a horizontal borehole going all the way through the crystal, into which the BC404 plastic scintillator cell for beta particle measurements is placed.

The BC404 plastic scintillator cell is a hollow cylinder of 54.3 mm length and an outer diameter of 14.7 mm. The cylinder wall is 1.2 mm thick and the endcaps are 2.5 mm thick. The inner surface of the cell is coated by a thin layer (425 nm) of aluminium oxide (Al_2O_3) in order to prevent the so-called “memory effect”, i.e. remnant activity that stays in a cell after a sample is evacuated, due to diffusion of xenon atoms into the plastic scintillator (Bläckberg et al., 2013). The volume of the cell is ~6.3 cm^3 and a typical sample composition from the SAUNA processing system, to which the cell is connected, is 1.2 cm^3 (STP) of stable xenon mixed with helium carrier gas at ambient pressure (1 bar). The cell is read-out by two gain-matched PMTs (Hamamatsu) coupled at each end of the cell using optical silicon pads. The typical gamma resolution is around 11% at 81 keV (key-gamma line of Xe-133) and beta resolution is ~35 keV at 129 keV (CE of Xe-131m).

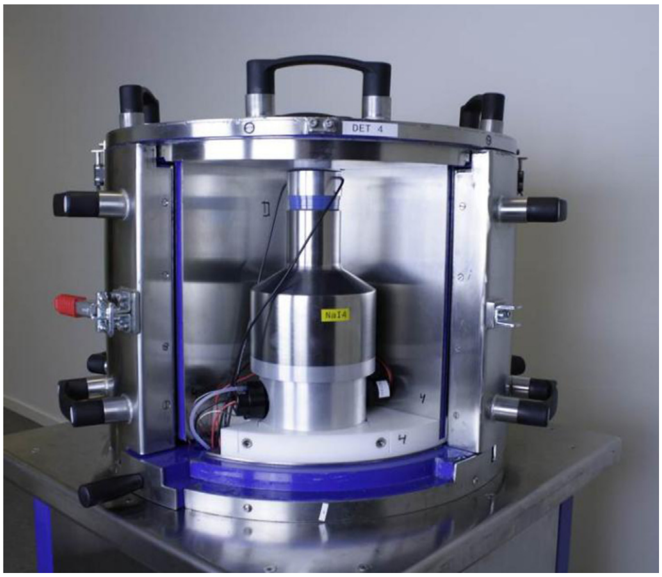

Fig. 1. OSI-SAUNA system detector.

The IMS SAUNA detector shielding is a 10 cm thick stainless steel double-walled barrel filled with lead shots, internally lined with 5 mm of copper and 5 mm of tin (the latter two in order to absorb the lead X-rays induced by cosmic muon radiation).

The latest SAUNA detector system was developed specifically for On-Site Inspections and comprises a clover configuration with four detectors with shorter PMTs, all housed in one modularized lead shield (solid parts, not shots) that can be assembled by two persons and in which any individual detector (NaI or plastic cell) can easily be replaced.

The data acquisition system is based on the Pixie-4 digital acquisition card (XIA, US) together with custom made software.

2.3. The Lares SiPIN detector system

The Lares Silicon PIN diode detector system (SiPIN) is a standalone nuclear detection system that can be connected to any of the existing NG systems (Fig. 2a). The beta particle detector comprises 6 commercially available gain-matched square silicon PIN diodes, 500 micron thick, with active area of 2.25 cm^2 large and arranged in a cube cell inside of which the sample is located. The diodes are held into place with an open grid type of arrangement made of PVC, which has been optimized to be as small as possible in order to reduce X-ray absorption. The diode cube arrangement is in turn inserted into an outer shell, a cube made of 0.5 mm thick aluminium, in order to withstand the vacuum during a sample evacuation. The interior volume is 7 cm^3 for the processed NG sample with 20% dead (inactive) volume. In the original configuration, the SiPIN cell, i.e. the cube, is placed in a well-type NaI cylinder of 50 mm length and 50 mm diameter, with a 28 mm deep well (diameter 28 mm). The NaI and each diode is readout separately by a custom-made digital 8 channel (one spare channel) MCA with an integrated high voltage supply. The software is custom made and supports list mode data acquisition with a resolution of 20 ns.

While the gamma resolution is the same as for the SAUNA detector, the beta resolution of the SiPIN detector is considerably improved, and even decreases with energy of electrons: ~13.5 keV at 129 keV and around 11 keV at 199 keV.

The small size of the NaI crystal originally provided by Lares makes the system less sensitive to the 250 keV gamma-ray of Xe-135. In an attempt to improve this sensitivity the SiPIN cube was also tested with a SAUNA NaI crystal described above (Fig. 2b).

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