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Reliability improvement for anisotropic biased compensated α/β contamination meter

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ABSTRACT

Nuclear instruments such as alpha/beta contamination meter are frequently used in a compensated mode where the contribution of gamma radiation background is compensated by a guard detector. The signal of interest is then the subtraction of counting from both channels. In practice, the noise signal measured by the guard detector is not strictly equal to the noise contribution into the first detector due to anisotropic biases.

The random error (under Poisson assumption) is taken into account to build a hypothesis test. The system is also designed to minimize the systematic error but in some cases, this bias could not be completely removed. The measurement system then shows different behavior when the surrounding environment changes exhibiting inopportune false alarms.

A method allowing the false alarms to be suppressed is addressed in this study for compensated measurement. An improvement in terms of reliability has been proven.

1. Introduction

Surface contamination is a major risk for workers in nuclear facilities, where an accidental leak of radionuclides can occur (nuclear power plants, fuel cycle, radioisotope, waste storage, nuclear weapon, decommissioning or research facilities). Monitoring alpha and/or beta particles from a contaminated surface by suppression the gamma radiation background is a challenging task.

The usual way to comply with this requirement is to perform discrimination between charged particles and gamma rays, where each event is classified by using pulse-height or pulse-shape discrimination. Pulse-height discrimination cannot be applied in beta contamination meter, since secondary electrons (from gamma rays) and beta particles cannot be distinguished through their energy deposition in the detector. Moreover, their equivalent let also hinders pulse-shape discrimination.

Beta and alpha particles are directly ionizing radiation and, at macroscopic level, they can be considered as interacting continuously with matter (i.e., through the continuous slowing-down approximation), while gamma rays are indirectly ionizing and more penetrating. Their attenuation in matter can be described through an exponential relation which depends on the attenuation length. Regarding this particularity, phoswich detectors exploit the different interaction mechanism of charged particles and gamma rays [1–5]. The strength of such a method is that the detector is intrinsically without isotropic bias. Phoswich is a reliable technique to address alpha/beta contamination meter. However, the intrinsic detection efficiency of beta particle is not equal to 100% due to a non-null overlap between gamma and beta events. Indeed, as the probability of gamma rays to interact with the first layer is nonzero, these gamma events cannot be discriminated from beta events. Moreover, this phenomenon is amplified by the poor energy resolution of the scintillator (low deposited energy, low optical efficiency). In order to address this effect, the number of gamma events contained in the overlap area is estimated using a proportionality factor between the gamma region and this overlap area. The technique contains a hidden compensation and could not be considered strictly a discrimination technique.

For a given detection surface, a fully compensation-based technique is more efficient for providing an intrinsic efficiency equal to 100% and could be implemented into alpha/beta contamination meters [6,7]. This technique consists in compensating the gamma radiation background by a guard detector located close to the reference detector. As illustrated in Fig. 1, the reference

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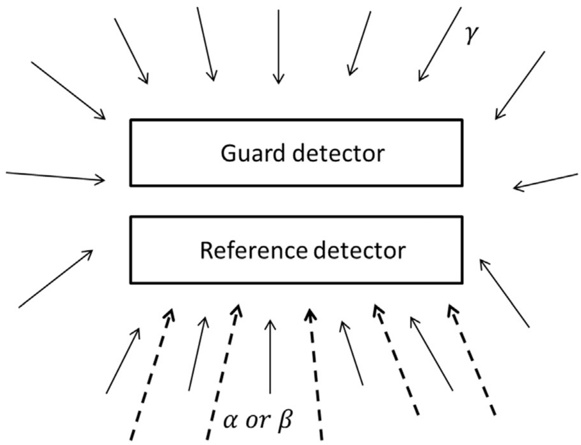

Fig. 1. Schematic view of the compensated detector.

detector houses a thin window, which allows the alpha and beta particles to interact with its sensitive zone. The guard detector is shielded by the reference one against beta and alpha particles. The signal of interest is obtained by subtracting the counts from both detectors.

Despite its excellent intrinsic efficiency, the compensation technique suffers from two drawbacks:

- The increase of the counting variance due to the subtraction (degradation of precision).
- The addition of an anisotropic bias, especially when a gamma ray hot-spot occurs close to the measurement position (degradation of accuracy).

A method has been developed to improve the reliability of such compensated measurements and will be described in details in the following Section.

2. Methods

2.1. The hypothesis test

The beta count rate is estimated by basing on a hypothesis test where H_0 is the null hypothesis (no beta count) and H_1 is the detection hypothesis (presence of beta counts).

Let $\hat{\lambda}_{comp}$ be the compensated count rate estimation, $\sigma^2(\lambda_{comp})$ its associated variance, $\hat{\lambda}_\beta$ the estimated beta count rate, and K_α a coverage factor (threshold) where α is the probability of false detection such that $\alpha \overset{\text{def}}{=} P(H_1 | H_0)$. Then the test for estimating $\hat{\lambda}_\beta$ is:

Algorithm 1.

If $\hat{\lambda}_{comp} > K_\alpha \sigma(\lambda_{comp})$
Then $\hat{\lambda}_\beta = \hat{\lambda}_{comp}$ (H_1 accepted and H_0 rejected)
Else $\hat{\lambda}_\beta$=0 (H_0 accepted and H_1 rejected)
End

2.2. Ideal compensation

Considering a perfect isotropy of the background flux, the compensated count rate λ_{comp} is calculated by subtracting the background signal λ_{guard} from the raw signal λ_{ref}:

$$\hat{\lambda}_{comp} = \hat{\lambda}_{ref} - \hat{\lambda}_{guard} \tag{1}$$

The random variance $\sigma^2(\lambda_{comp})$ is calculated as the sum of both individual variances (by assuming statistical independence):

$$\sigma^2(\lambda_{comp}) = \sigma^2(\lambda_{ref}) + \sigma^2(\lambda_{guard}) \tag{2}$$

It should be noted that, according to Eq. (2), the fluctuation of the signal is increased for a compensated measurement compared with single-channel measurement. This precision discrepancy associated to $\hat{\lambda}_\beta$ also influences the detection limit (see Algorithm 1). A critical point for the compensated measurement is therefore the smoothing of individual counting signals $\hat{\lambda}_{ref}$ and $\hat{\lambda}_{guard}$ with a convenient filter. Nonlinear filters have been developed to provide the best trade-off between precision and response time for such nuclear counting measurement [8]. The implementation of a nonlinear filter is fundamental for maintaining competitive performance compared to other beta contamination meter techniques.

2.3. Non-ideal compensation

Actually, the reference and the guard detectors have not exactly the same gamma sensitivity. This effect can be modeled by adding a compensation factor θ, by taking into account the difference in gamma ray response between the reference and the guard detector.

$$\hat{\lambda}_{comp} = \hat{\lambda}_{ref} - \theta\hat{\lambda}_{guard} \tag{3}$$

Thus, the variance $\sigma^2(\lambda_{comp})$ results to be:

$$\sigma^2(\lambda_{comp}) = \sigma^2(\lambda_{ref}) + \theta^2\sigma^2(\lambda_{guard}) + \lambda_{guard}^2\sigma^2(\theta_E) \tag{4}$$

The variance associated to the compensation factor $\sigma^2(\theta_E)$ is due to the dispersion of the value of θ as a function of the energy E of the incident gamma rays. This phenomenon is observed when the two detectors are made of different materials or different shielding. The variance $\sigma^2(\theta_E)$ could be calculated with Monte Carlo simulations, by basing on experimental data, and with the method described in Ref. [9]. In the case of an α/β contamination meter, where the same technologies of detectors are used and where both detectors are encapsulated in a shield made of an equivalent material, the variance $\sigma^2(\theta_E)$ could be neglected. Eq. (4) becomes:

$$\sigma^2(\lambda_{comp}) = \sigma^2(\lambda_{ref}) + \theta^2\sigma^2(\lambda_{guard}) \tag{5}$$

2.4. The anisotropic bias

The values of θ can be distributed as a function of the angle of incidence φ of a gamma ray hot-spot and its distance d from the hot-spot source ($\theta_{\varphi,d}$). This effect depends on the anisotropy of gamma rays and on the mutual shielding effect of the two detectors. Taking into account these phenomena, the compensated measurement $\hat{\lambda}_{comp}$ is expressed by Eq. (3), and its associated variance becomes:

$$\sigma^2(\lambda_{comp}) = \sigma^2(\lambda_{ref}) + \theta_{\varphi,d}^2\sigma^2(\lambda_{guard}) + \lambda_{guard}^2\sigma^2(\theta_{\varphi,d}) \tag{6}$$

The calculation of the variance of the compensation factor $\sigma^2(\theta_{\varphi,d})$ without any *a priori* information leads to its divergence (when $d \to 0$, $\sigma^2(\theta_{\varphi,d}) \to \infty$) and to a zero estimate of beta counts (see Algorithm 1).

In order to deal with this difficulty, a model should be