

RESEARCH ARTICLE

Energy Resolution Stability of a NaI(Tl) Detector Using ^{137}Cs Source

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ABSTRACT

The energy resolution is one of the most important performance parameters of scintillation detectors, and it characterizes their ability to accurately measure gamma-ray energies. In this study, the statistical stability of the energy resolution of a NaI(Tl) scintillation detector was investigated using gamma spectra from a ^{137}Cs source under fixed operational conditions. The energy resolution was determined from the full width at half maximum (FWHM) of the photopeak and analyzed using statistical methods.

Approximately 100 spectra were acquired and analyzed in the R environment using descriptive statistics, normality tests, correlation, and regression analyses. The results show a mean energy resolution of 16.94 ± 0.81 , indicating low dispersion and stable detector performance. Although a statistically significant relationship with the measurement sequence was observed, the low coefficient of determination ($R^2 = 0.24$) suggests that the variations are mainly due to inherent statistical fluctuations.

Overall, the findings confirm that the NaI(Tl) detector exhibits stable performance under controlled laboratory conditions and demonstrate the effectiveness of statistical time-series analysis for evaluating detector stability.

Keywords: NaI(Tl) detector; ^{137}Cs source; energy resolution; gamma rays; R environment; Q-Q plot

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1. Introduction

The detection and measurement of gamma radiation play a crucial role in nuclear physics, radiation metrology, and applications in medical, industrial, and environmental fields [1]. One of the key performance parameters of radiation detectors is energy resolution, which reflects the detector's ability to distinguish between gamma-ray energies and accurately identify spectral features [2]. The performance and stability of scintillation detectors are influenced by several factors, including detector design, source geometry, associated electronics, and data acquisition methods.

NaI(Tl) scintillation detectors are widely used due to their high detection efficiency, relatively simple structure, and good response over a wide range of gamma-ray energies [3]. The use of photomultiplier tubes (PMTs) with NaI(Tl) crystal enables efficient light collection and signal amplification, allowing reliable measurements under various experimental conditions. Additionally, these detectors exhibit low intrinsic background, which facilitates the detection of low-energy radiation with reduced electronic noise [4].

Several studies have investigated the performance of NaI(Tl) detectors using ^{137}Cs sources. Arectout et al. [5] reported good agreement between experimental measurements and simulations using

GAMOS and FLUKA, particularly for photopeak characteristics and energy resolution. Zhou et al. [6] analyzed detector response using the EACY-MCA 2K system and demonstrated that variations in energy resolution are related to changes in photomultiplier tube response. Similarly, Maeng et al. [7] evaluated detector performance in the low-energy range using Maestro-based analysis, achieving stable efficiency ratios while accounting for X-ray escape effects.

Despite these contributions, limited attention has been given to the statistical stability of energy resolution under repeated measurements using a ^{137}Cs source. In particular, the role of statistical fluctuations and their impact on the reproducibility of detector performance has not been sufficiently addressed using systematic statistical approaches.

Therefore, the present study aims to evaluate the statistical stability of the energy resolution of a NaI(Tl) detector using repeated gamma-ray spectra from a ^{137}Cs source. Standard statistical methods, including descriptive analysis, normality testing, correlation, and regression, are applied using the R environment to assess the consistency and reliability of the detector response under controlled experimental conditions.

2. Experimental

A 3×3 inch NaI(Tl) scintillation detector was positioned at a distance of 7 cm from a ^{137}Cs source, as illustrated schematically in Figure 1. The distance was selected to provide sufficient photon flux for reliable counting statistics while minimizing dead time effects [8]. The ^{137}Cs source was chosen due to its well-defined gamma emission at 662 keV, which serves as a standard reference for energy calibration and detector performance evaluation, particularly for NaI(Tl) detectors under typical laboratory conditions.

The detector was operated at a high voltage of 820 V to ensure stable and optimal performance during spectra acquisition. Energy calibration was carried out using a standard gamma-ray source to establish the relationship between photon energy and the channel number.

Approximately 100 spectra of the ^{137}Cs source were collected, with an acquisition time of 500 s per spectrum. This acquisition time was selected to ensure adequate counting statistics while minimizing the fluence of electronic noise and background radiation. The dead time was monitored during the measurements and was found to be negligible under the selected experimental conditions.

Background radiation was measured prior to the experiment and subtracted from the recorded spectra [9,10].

The gamma-ray spectra were analyzed using Maestro software (version 1.1.463) to extract the energy resolution (ER%), full width at half maximum (FWHM), and peak position (PP). Statistical analyses were performed using the R software environment (version 4.x) through R Studio. Standard statistical parameters, including the mean and standard deviation, were calculated to evaluate the stability and reproducibility of the detector response.

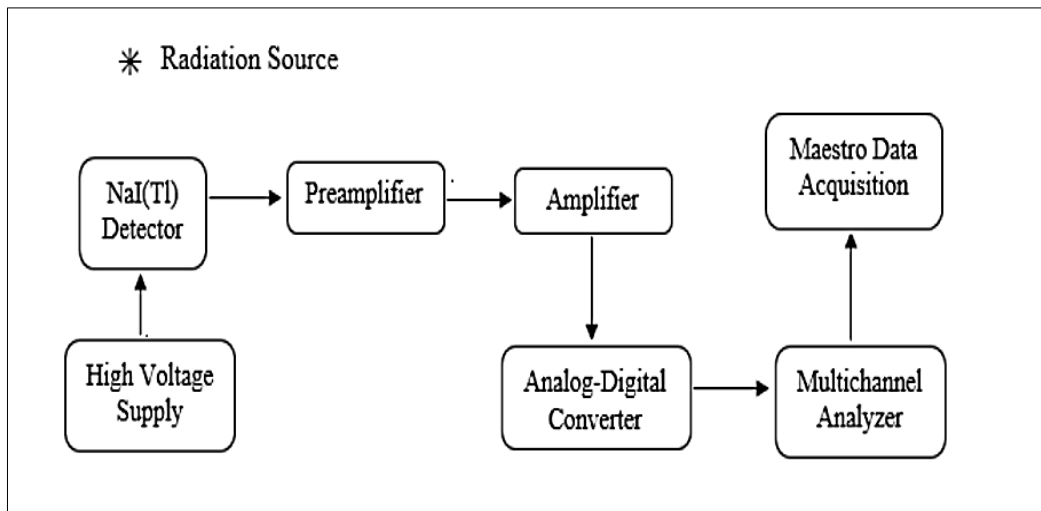


Figure 1. Block diagram of a NaI(Tl) scintillation detection system and signal processing chain (adapted from ^[11])

3. Results and Discussion

This section presents the results of the statistical analysis of the energy resolution obtained from the recorded ¹³⁷Cs spectra. Approximately 100 spectra were collected under controlled experimental conditions (operating voltage and acquisition time) to evaluate the stability of the detector’s performance. Several statistical methods were applied, including mean, median, standard deviation, along with normality testing, and correlation and regression analysis. The main results are presented in Table 1.

Table 1. Statistical analysis results of energy resolution (ER%)

Result	Value (%)
Min	14.78
1st Qu.	16.48
Median	16.54
Mean±SD	16.94±0.81
3rd Qu.	17.31
Max	19.47
Variance	0.66
Coefficient of variation (CV%)	4.78%

The energy resolution can be expressed as $16.94 \pm 0.81\%$, indicating a moderate level of fluctuation in repeated measurements at 662 keV (¹³⁷Cs gamma energy). The coefficient of variation (CV%) was calculated as $CV = SD/Mean \times 100\%$ and found to be 4.78%, confirming a low relative dispersion of the measured value. This small standard deviation and low CV% suggests that the detector response remains stable under constant operating conditions during the acquisition of ¹³⁷Cs spectra.

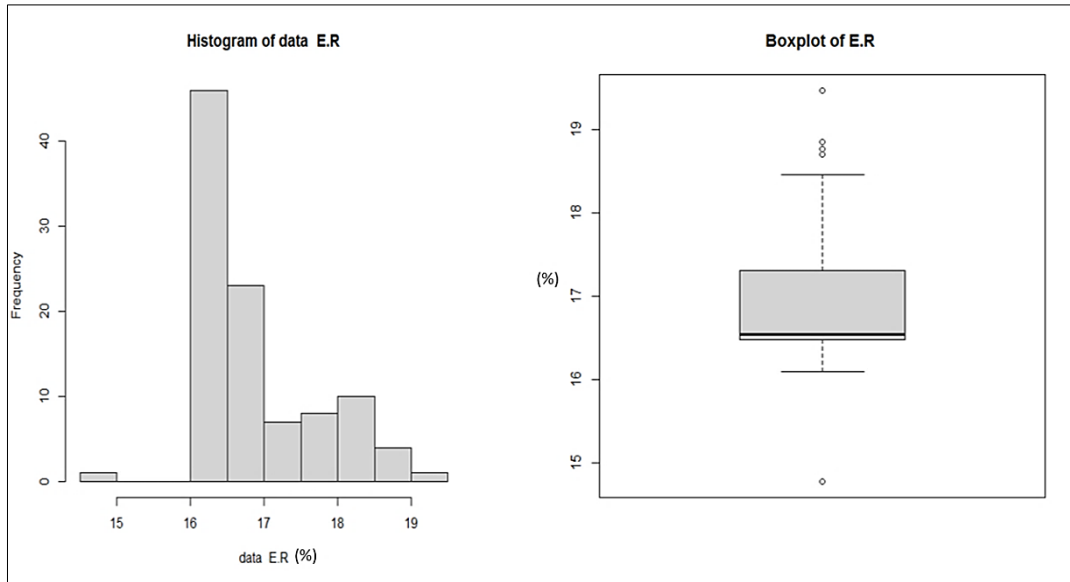


Figure 2. Histogram and boxplot of energy resolution (ER%) distribution

The histogram and boxplot in Figure 1 indicate that the energy resolution values are centered around the mean, with a small number of outliers. These outliers may be attributed to statistical fluctuations in scintillation light production and signal generation in the photomultiplier tube, rather than any systematic effects in the detector performance.

Table 2. Normality assessment using the Shapiro-Wilk test

Factor	W statistic	p-value
Energy Resolution (ER%)	0.78	1.80×10^{-10}
Measurement sequence (number of spectra)	0.95	0.001

The Shapiro-Wilk results presented in Table 2 indicate that the energy resolution (ER%) data deviate from a normal distribution, as evidenced by the very low p-value ($p \ll 0.05$). A similar deviation is observed for the measurement sequence. This non-normal behavior can be attributed to the statistical nature of scintillation processes, where the number of detected photons follows Poisson statistics, especially when considering small fluctuations between successive spectra. Therefore, the observed distribution reflects inherent counting statistics rather than experimental instability. This result suggests that caution should be exercised when applying parametric statistical methods.

Table 3. Results of the Pearson correlation analyses

Relationship	t-statistic	p-value	Correlation coefficient (r)
Energy resolution (ER%) vs. measurement sequence (number of spectra)	5.68	1.38×10^{-7}	0.50

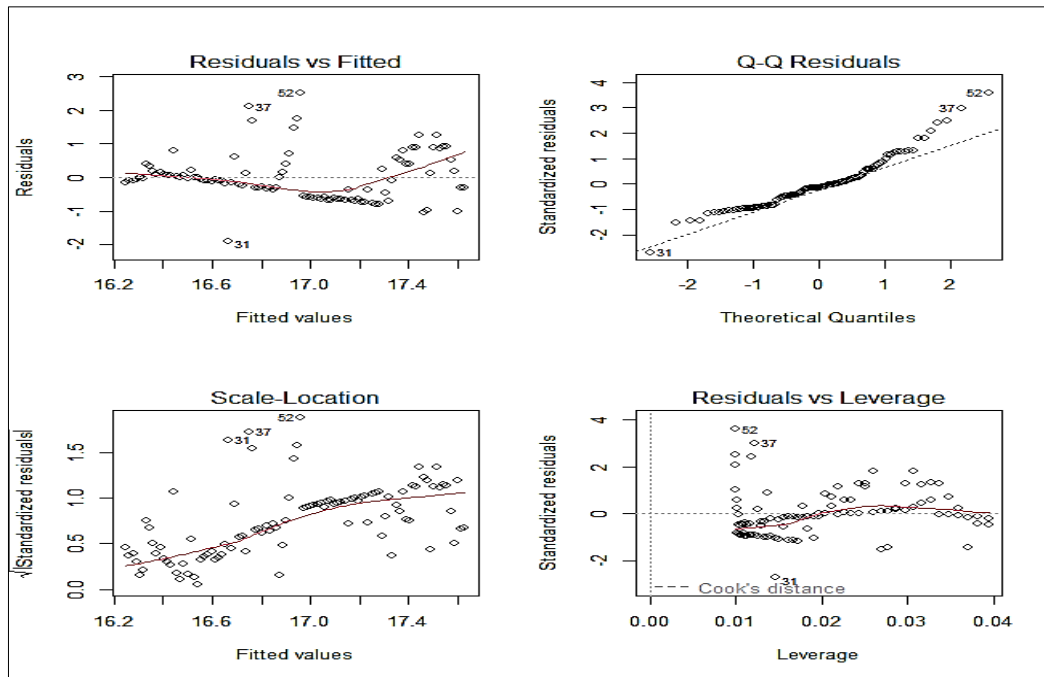
Table 3 presents the Pearson correlation coefficient (r) between the measured energy resolution values and the measurement sequence. The obtained correlation ($r = 0.50$) indicates a moderate relationship; however, this should not be interpreted as a direct physical dependence. Instead, it likely reflects statistical averaging and improved peak estimation with repeated measurements. Considering the non-normal distribution of the data, this result should be interpreted with caution when applying parametric statistical methods.

Table 4. Simple linear regression results for energy resolution (ER%)

Parameter	Value
Intercept (Estimate)	16.24
Slope	0.014
F-statistic	32.26
R ²	0.24
p-value	1.38×10 ⁻⁷

Results of the linear regression presented in Table 4 indicate a statistically significant linear relationship between energy resolution (ER%) and the measurement sequence ($p \ll 0.05$). However, the coefficient of determination ($R^2 = 0.24$) is relatively small, indicating that only a limited portion of the variation in ER% is explained by the model. This suggests that the observed trend does not reflect a direct physical dependence, but is more likely associated with statistical fluctuations and improved counting statistics arising from repeated measurements.

Validation plots for the linear regression model (Figure 2), including residuals vs. fitted values, Q–Q, and scale–location plots, indicate that the observed variance is primarily due to random statistical fluctuations, with no systematic pattern suggesting model bias or measurement errors. Although some points exhibit relatively high leverage, they do not have a significant influence on the overall model.

**Figure 3.** Diagnostic plots of the linear regression

The observed stability of the energy resolution, derived from the full width at half maximum (FWHM) and peak position (PP), can be attributed to the underlying physical processes governing scintillation detection. These include photon statistics, detection efficiency, photomultiplier tube response, and electronic noise, all evaluated under constant experimental conditions.

4. Conclusion

The statistical analysis indicates that the observed fluctuations in energy resolution are primarily governed by the inherent stochastic nature of the scintillation process, with only minor contributions from electronic noise and other experimental factors. The relatively low dispersion ($16.94 \pm 0.81\%$) confirms the

stability of the NaI(Tl) detector during the acquisition of ^{137}Cs gamma spectra under constant operating conditions.

Although the results show a statistically significant relationship between energy resolution and the measurement sequence, the low coefficient of determination ($R^2 = 0.24$) indicates limited predictive power, suggesting that the variations are mainly driven by statistical fluctuations rather than a strong systematic effect.

Overall, these findings demonstrate that NaI(Tl) detectors provide stable performance in controlled laboratory environments and highlight the usefulness of statistical time-series analysis, implemented in the R environment, for evaluating detector stability.

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