Feasibility study of a Compton Suppression system for the X-ray Fluorescence (XRF) using Monte Carlo simulation

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1. Introduction

Quantifying the plutonium contents in spent nuclear fuels, recovered U or U/TRU products is necessary in safeguards [1,2]. The x-ray fluorescence (XRF) technique is one of the non-destructive assay (NDA) techniques used to quantify the Pu contents [3]. The XRF technique compares the measured pulse height of U and Pu peaks which are self-induced characteristic x-ray emitted from U and Pu to quantify the elemental U and Pu [2]. The measurement of the U and Pu x-ray peak ratio provides information on the relative concentration of U and Pu elements. Photon measurements of spent nuclear fuel using high resolution spectrometers show a large background continuum in the low energy x-ray region in large part from Compton scattering of energetic gamma-rays. The high Compton continuum can make measurements of plutonium x-rays difficult because the relatively small signal to background ratio produced. In pressurized water reactor (PWR) spent fuels with low plutonium contents (~1%), the signal to background ratio may be too low to get an accurate plutonium x-ray measurement. The Compton suppression system has been proposed to reduce the Compton continuum background. In the present study, the feasibility of a Compton suppression system for XRF was evaluated by Monte Carlo simulations and measurements of the radiation source.

2. Compton Suppression System

2.1Experimental Setup

The LEGe (Low Energy High purity germanium) main detector and BGO (Bismuth Germanate) guard detector were used to configure the Compton suppression system. The LEGe detector is a planar type with a diameter 8 mm and a length of 10 mm (ORTEC, GL0210), and its bias voltage is optimized at a negative 1000 V [4]. The BGO scintillator of a cylindrical with a diameter of 156 mm and a length of 65 mm, is a well-type in that the LEGe detector can be combined vertically to the BGO detector. The light output from the BGO scintillator is collected by a 5 inch photomultiplier tube (PMT) at an applied high voltage of a positive 1000 V. The dimensions and experimental setup of the BGO escape-suppression shield and the LEGe detector are shown in Fig. 1.

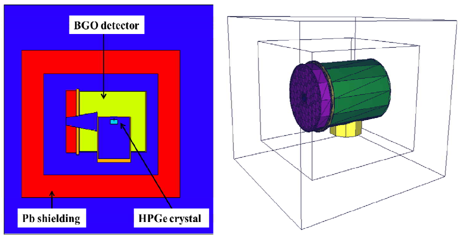

Fig. 1. The dimensions and experimental setup of the BGO escape-suppression shield and the LEGe detector.

Elimination of Compton scattered events that could not make photo-peaks in the LEGe detector is made by using coincidence electronics to reject gamma-rays that escaped from the LEGe main detector. Two timing signals, one from the LEGe main detector and the other from the BGO guard detector, are fed to an ORTEC CO4042 coincidence module. In this experiment, a coincidence time width of 500 ns is chosen, and the timing signals forming the LEGe detector are delayed by about one half the width of the coincidence time width. When the two timing signals are in coincidence, the coincidence unit generates one signal, and then these signals are fed to the coincidence unit with LEGe timing signals. Whenever these two signals are in anti-coincidence, the ORTEC GG8020 module makes a TTL (Transistor-Transistor-Logic) signal as long as the energy signal of the LEGe detector's main amplifier. As a result, the output signals are rejected by Compton-scattered events and then used as a gate for obtaining a Compton suppressed energy spectrum. Figure 2 shows the schematic diagram of the electronics for the processing signals in a Compton suppression system.

2.2Compton Suppression System Simulation

To evaluate the system, MCNP simulations were performed using the same geometry of the experiments, as shown in Fig.1. The modeling of a system that considers the production of the secondary electrons and photons for precise results was performed. A coincidence particle, which is reacted with both a LEGe detector and a BGO detector, is rejected, and a particle reacted with only a LEGe detector is recorded as an available signal. Because the detector dead time and the temporal resolution of the system were not considered in the simulation modeling, the results of the simulations were expected to have more well-suppression than those of the experiments.

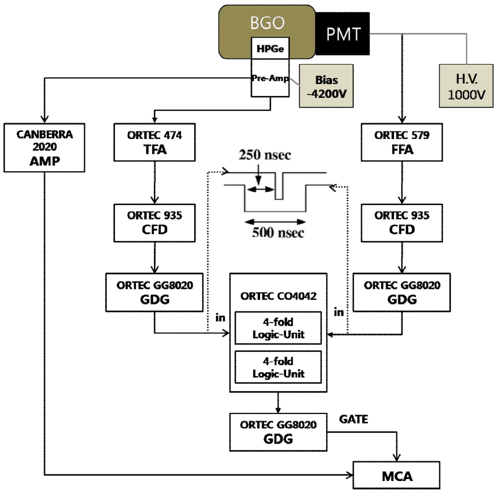

Fig. 2. Schematic diagram of the electronics for the processing signals used in a Compton suppression system. AMP: Spectroscopic amplifier, TFA: Timing filter amplifier, FFA: Fast timing filter amplifier, CFD: Constant fraction discriminator, GDG: Gate and delay generator, MCA: Multi-channel analyzer.

2.3 Preamplifier Model

The threshold energy of the BGO guard detector is sensitive for the performance of Compton suppression, and is usually set to a low level because Compton scattered gamma-rays have lower energy ranges. In this experiment, we used a threshold level of 250 mV, which corresponded to ~ 50 keV according to the energy calibration of the BGO guard detector. The pulse height spectra were obtained for the standard ^{137}Cs gamma-ray source with and without the Compton suppression system, as shown in Fig. 3.

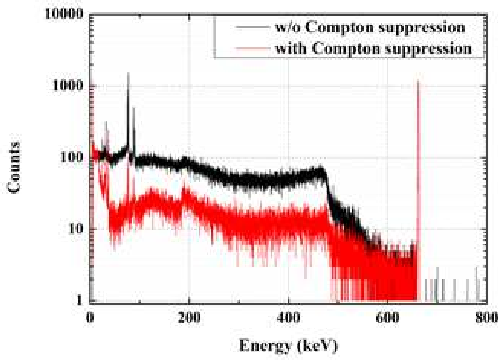

Fig. 3. Gamma-ray pulse height spectra obtained with standard ^{137}Cs gamma-ray source.

In the suppression spectrum, the Compton continuum of the whole range of gamma-ray energies under the photo-peaks is compressed using the BGO guard detector. As a figure of merit to evaluate the gamma-ray detection, the factor of the peak-to-total ratio is considered, which is the ratio between the number of photo-peak counts to the number of total counts. . As a result, the peak-to-total ratio was enhanced by a factor of two or more when the Compton suppression system was used.

Fig. 5 (a) shows the measured spectra for ^{60}Co gamma-ray source with and without Compton suppression system and its comparison with the MCNP simulation results. The measurement results for the gamma-ray energies from ~ 300 keV to ~ 500 keV are in good agreement with the simulation results.

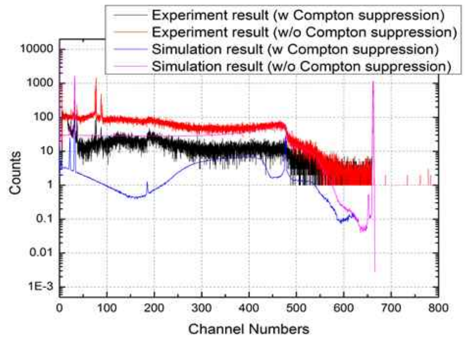

Fig. 3. . Results of experiment and simulation for ^{137}Cs gamma-ray source with and without Compton suppression

3. Conclusions

In this study, the feasibility of a Compton suppression system for XRF was evaluated by MCNP simulations and measurements of the radiation source. Experiments using a standard gamma-ray source showed that the peak-to-total ratios were improved by a factor of three when the Compton suppression system was used. According to the performance of the MCNPX simulation, the suppression ratios for the measurements of spent nuclear fuels were more than a factor of five. This result shows the feasibility of a Compton suppression system to the XRF technique.

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