Installation and Testing of a Compton Suppression System

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Introduction

The three major interaction mechanisms of gamma-rays with matter are photo-electric absorption, Compton scattering, and pair production. In all of these interactions, the gamma-ray photon energy is partially or completely transferred to an electron. During photoelectric absorption, the photon interacts with an atom and the photon completely disappears. In the Compton scattering mechanism, the gamma-ray interacts with an electron, causing an increase in the electron's energy. A new gamma-ray with a lower energy is then emitted. The new gamma-ray can escape from the material in which it was formed or can be absorbed through the photoelectric effect. During pair production, high-energy gamma-rays are absorbed and two particles are created (an electron and a positron) that share the energy of the gamma-ray. The positron subsequently loses its energy through ionization or excitation. If it is stationary, the positron interacts with an electron creating two gamma-rays with energies of 511 keV each (annihilation radiation). These two gamma-rays can escape or interact with matter through the Compton scattering or Photoelectric effect. Pair production does not occur below 1.022 MeV. The Compton effect is the predominant effect at intermediate gamma-ray energies (200 keV to several MeV).

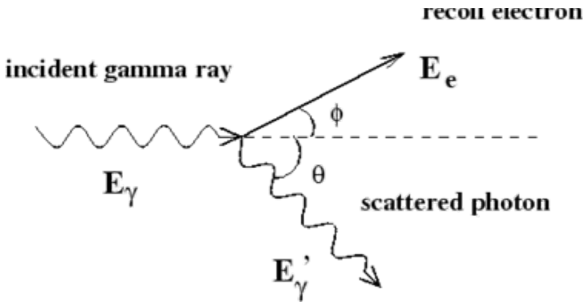

FIGURE 1: The Compton Scattering process

The vast majority of the scattered photons in Compton scattering escape the detector, causing background counts in the gamma spectrum. If all of the energy of the incident photon is not absorbed in the detector, then there is a continuous background in the energy spectrum, known as the Compton continuum. This continuum extends up to an energy corresponding to the maximum energy transfer, where there is a sharp cut-off point, known as Compton edge.

In order to reduce the contribution of scattered gamma-rays to the detected background, the detector can be surrounded by a separate guard detector. The two detectors are operated in anti-coincidence mode, which means that if an event occurs at the same time in both detectors, then the event is rejected. The guard detector catches the escape photons and the effect of those photons is subtracted from the background of the primary detector. Thus, Compton suppression systems (CSS) provide a tool to suppress unwanted background levels, providing improved detection for isotopes with energies in the range of the reduced Compton continuum. The combination of a central high purity germanium (HPGe) detector and a sodium iodide (NaI) guard detector is called a Compton suppression spectrometer.

Coincidence and Anti-Coincidence Measurements

Coincidence and anti-coincidence are detection modes used to produce a simplified spectrum from certain types of detector systems. In a system of two detectors, each detector produces separate signals. In coincidence mode those signals are counted. In anti-coincidence the signals produced at the detectors cancel or veto each other, leaving the non-coincident signals to be counted. The advantage of coincidence or anti-coincidence techniques is achieving greater accuracy in the determination of full energy peaks in the spectrum.

The Penn State Compton Suppression System

The Penn State Compton suppression system (Figure 2) at the Radiation Science and Engineering Center includes:

- An HPGe detector with Canberra Model 3106D NIM bin and high voltage power supply
- A NaI guard detector in a lead shield with a Canberra Model 2100 NIM bin and power supply
- PC desktop
- Canberra Genie 2000 software

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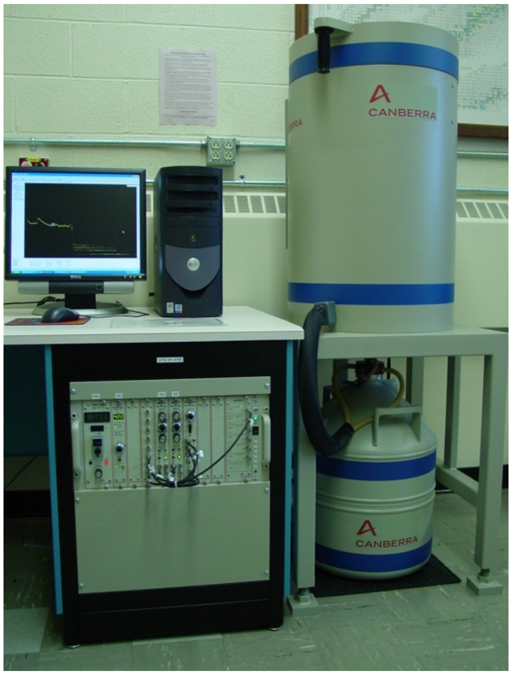

FIGURE 2: Penn State's Compton suppression system

TABLE 1: Penn State Compton suppression system properties

Relative efficiency	54%
Resolution	2.2 keV (FWHM) at 1.33 MeV
Peak/Compton	58:1
Diameter	64 mm
Length	71 mm
Vertical slimline dipstick cryostat	• 2.5" endcap • 4" remote detector chamber • Ultra low background cryostat hardware

The HPGe detector is a reverse electrode, closed-end coaxial germanium detector, whose properties are given in Table 1.

The suppression of Compton events can only be as good as the ability of the guard detector to detect the scattered photons. The NaI detector consists of an annulus and a plug (Figure 3). The addition of the plug above the sample greatly reduces the Compton continuum, allowing for increased detection of isotopes in the continuum energy range.

Test Results

A ^{137}Cs source was counted using the CSS. The peak to Compton ratio, which is the ratio of the full energy peak to the energy of the Compton continuum, is calculated in order to determine the performance of the system. Equation 1 shows the specific energies used as markers within the spectra to calculate the peak to Compton ratio. Figure 4 shows the comparison between counting when suppression (SUP) is on and when suppression is off (NOSUP).

FIGURE 3: Inside view of the CSS shield where plug detector and photomultiplier tubes can be seen

Another test was carried out using samples from the ongoing determination of trace element concentrations (in particular trace amount of gold) in dendrochronologically-dated tree ring samples using the Neutron Activation Analysis (NAA) technique at our facility. The ultimate objective of this study is to determine a correlation between annual uptake of gold and major environmental or climatologic changes (e.g. volcanic eruptions). Several thousand wood samples have been analyzed by employing conventional NAA. All samples used in this study have been independently dated by researchers at The Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University, where over 40,000 individually-dated wood samples with 4.5 million rings, spanning the period from 7000 BC to the present, are archived. Samples containing elevated levels of gold are being analyzed again for short and long half-life elements (e.g. silver, copper) to investigate other elemental signatures of environmental changes using the CSS. Elemental analysis of a wood sample from the Porsuk central Anatolian region of Turkey with 819 Relative Gordion Year was performed by using the CSS. The CTUPOR-819 wood sample was activated at 1 MW in the PSU Breazeale Nuclear Reactor and then counted in the CSS. Figure 5 shows the comparison of suppressed and unsuppressed spectra with determined gamma-ray peaks. As demonstrated in Figure 6, the 411.8 keV gold peak was buried in the Compton continuum without the suppression, whereas with the CSS, it was possible to resolve the gold peak.

Conclusions and Future Work

The Penn State CSS has shown excellent performance and has highlighted the role it can play in the improved detection of neutron activated isotopes with gamma-ray signals that are overwhelmed by the Compton continuum from other isotopes. However, there are a

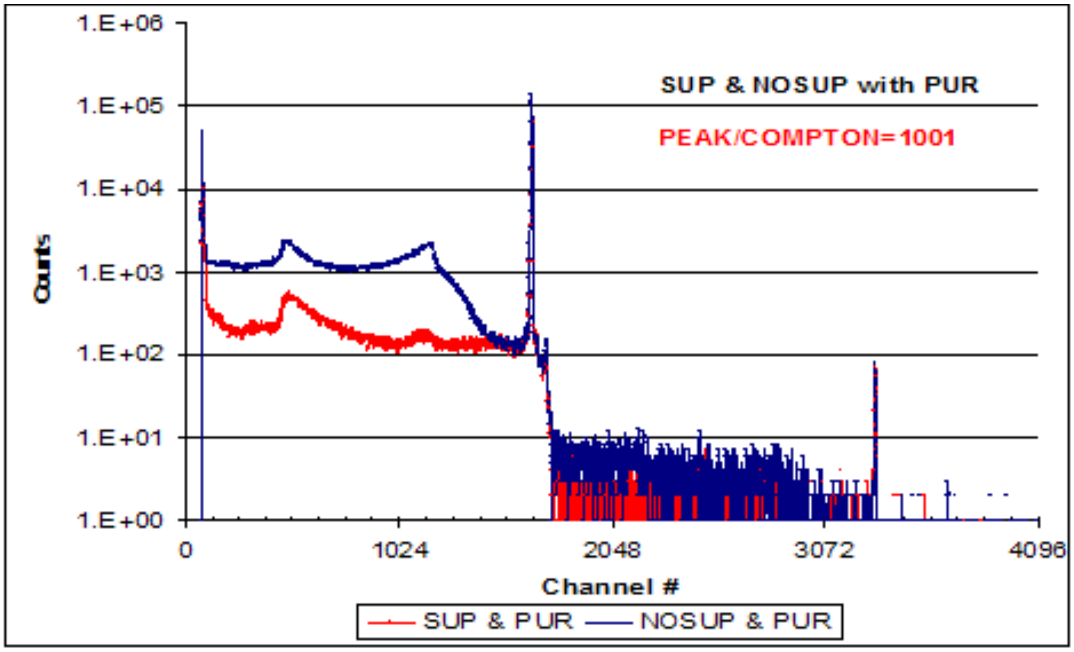

FIGURE 4: Spectra of ^{137}Cs counted with the Compton suppression system with suppression enabled (red) and disabled (blue), using pile up rejection.

$$\frac{Peak}{Compton}=\frac{\text{Number of counts in the highest channel of the 662.2 keV peak}}{\text{Average of the number of counts in the channels at 396 and 422 keV}}=1001 \qquad (1)$$

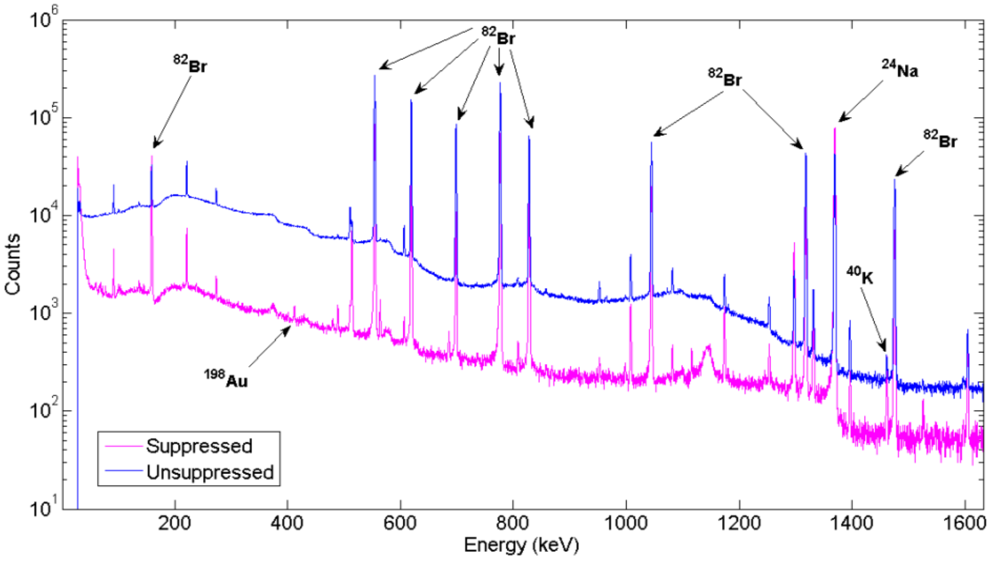

FIGURE 5: Comparison of CTUPOR3-819 wood sample gamma-ray spectra with and without Compton suppression

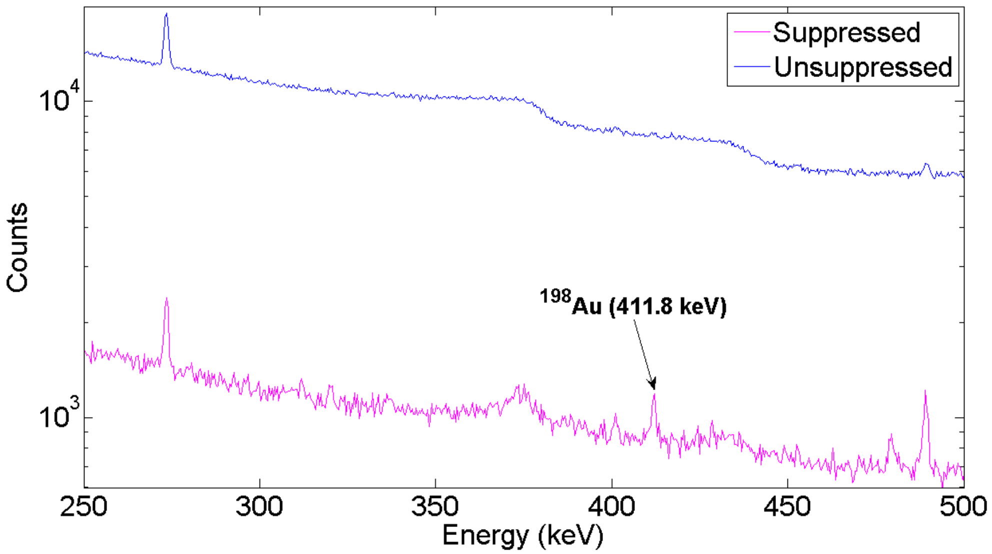

FIGURE 6: Expanded region of the CTUPOR3 spectrum showing the gold (Au) peak is visible using Compton suppression

number of improvements that can be made. Most importantly, elements that have decay cascades of gamma-rays must be accounted for.

A radioactive nucleus in an excited state can reach the ground level through single or cascade gamma-ray emissions. Since the gamma-rays are emitted isotropically, there is a probability due to the geometry of the Compton suppression system, that successive gamma-rays in a cascade process will be registered in different detectors. If the gamma rays are temporally separated by a tiny fraction of time, the counts will be falsely eliminated by the anti-coincidence circuit resulting in suppression of the full energy peak.

Therefore, two separate efficiency calibrations must be used for the suppressed and unsuppressed modes. In the unsuppressed mode, both single and cascade gamma-ray emitters can be used in the calibration with a wide energy range. For the suppressed spectrum, an efficiency calibration based on the single emitters must be applied to any single emitter that is counted. The cascade emitters must be treated separately each with their own efficiency values. Irradiation of V, Mg, Al, Dy, Zn, Zr, Cu, Au, Nb, Mn foils that are single gamma-ray emitters is being planned. The efficiency calibration will be performed in the suppressed mode on the collected spectra and the selected cascade emitters will be individually evaluated. The calibration database will be then used to quantitatively determine the constituents of the tree-ring samples.