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Performance of a Compton Suppression Spectrometer of the SNU-KAERI PGAA Facility

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Abstract

The γ-ray spectrometer of the PGAA (Prompt Gamma Activation Analysis) facility constructed at HANARO of the Korea Atomic Energy Research Institute was upgraded to the multi-mode spectrometer including the single mode, the Compton suppression mode and the pair mode. The performance of the spectrometer was tested and summarized. The background count rate and the uncertainty of the detection efficiency were reduced greatly in comparison with those before the new installation.

Key Words : HPGe detector, BGO/NaI(Tl) guard detector, prompt gamma activation analysis, Compton suppression, efficiency calibration, channel-energy non-linearity calibration

1. Introduction

The γ-ray spectrum from thermal neutron capture is extremely complex and contains many photopeaks. Due to the large number of γ-rays incident on the detector, the associated Compton continuum is a significant hindrance for good spectroscopy. For example, the Compton continuum makes the search of low-intensity peaks difficult and increases the uncertainty of the measured activities. In this study, the prompt γ-ray measurements had been performed at the SNU-KAERI PGAA facility at HANARO of the Korea Atomic Energy Research Institute (KAERI). This facility was initially developed for the study of boron concentration analysis using a single bare HPGe detector[1]. In the upgrade of the facility, the reduction of the Compton continuum has been achieved by surrounding the germanium detector with guard detectors whose signals are used for the anti-coincidence gating in the analog-to-digital converter. In this paper, the improved performance of the Compton suppression γ-ray spectrometer is described.

2. Apparatus

The SNU-KAERI PGAA facility is operating at the ST1 port of the HANARO research reactor[2]. The facility is characterized by the unique polychromatic neutron beam obtained using the pyrolytic graphite crystals[3,4]. The effective neutron temperature is 269 K. The true integrated flux and the conventional thermal equivalent flux at the sample position are 7.9×10^7 n/cm^{2}s and 8.2×10^7 n/cm^{2}s, respectively. The cadmium ratio for Au is 266. The facility has been utilized for accessing the beam characteristics[3,4], the boron concentration analysis[3,5] and the measurement of the prompt k_0-factors for the strong non-$1/\upsilon$ absorbers[6] using the single bare HPGe detector and the associated electronics. After those studies on the several topics using the single bare HPGe detector, the facility has been upgraded to the multi-mode γ-ray spectrometer, which operates in the single, Compton suppression and pair modes by adding the BGO/NaI(Tl) guard detector and the associated electronics. A layout of the new arrangement around the detectors and surrounding shields is shown in Fig. 1. The arrangement is kept compact because of the space limitation. An n-type HPGe detector with a relative efficiency of 43% is located at 25 cm distance from the sample and placed at 90° with respect to the neutron beam direction in order to permit maximum shielding and low background as possible. The guard detector is a symmetry-type BGO/NaI(Tl) scintillator divided into the front and side parts. The front part is a NaI(Tl) scintillator and the side part consists of the optically isolated 8-segment BGOs. Each of the segments is coupled to a photomultiplier tube. The energy resolution (FWHM) of the guard detector is about 16%. The specification of the detectors is listed in Table 1. All parts of the detectors including the photomultiplier tubes are shielded by lead of 10 cm thickness at least and 4 mm thick borated plastic sheets. A lead-stepped collimator is located in front of the opening of the guard detector. The 4 mm thick ^{6}LiF tiles are placed at the entrance of the collimator to reduce the neutrons directly incident on the detector. Sample mount was made of aluminum and designed to unfold inside the lead shield to minimize the immersed part in the neutron beam. A block diagram of the electronics is shown in Fig. 2. The shaped signal of the germanium detector is sent to analog-to-digital converters having 16k multi-channel buffer. In the

Table 1. Specification of the Detectors

	HPGe detector	BGO/NaI(Tl) guard detector
Supplier	EG&G ORTEC	BICRON
Model	GMX30190-S	5.75HW6.30BGO/NaI(Tl)/(8)1.5-X
Crystal size	58.2 mm F × 79.0 mm L	-
Preamp or Photomultiplier tube	Resistive feedback type	HAMAMATSU 2060 38.1 mmϕ 8 tubes
Bias voltage	-3900 V	+700 V
Energy resolution or Pulse height resolution	1.8 keV (guaranteed) 2.2 keV (measured) (for 1332.5 keV from ^{60}Co)	16% FWHM (for 661.7 keV from ^{137}Cs)
Relative detection efficiency	43% (for 1332.5 keV from ^{60}Co)	-

single mode, all the signals from the germanium detector are stored. In the Compton suppression mode, conversions are performed only when no coincidence is met between the signals from the guard detector and the germanium detector. The time window for rejecting Compton events is 1200 ns. In the pair mode, the events are recorded when triple coincidence occurs between the germanium detector and the two halves of the BGO/NaI(Tl) crystals. Data collection and on-line analysis of the spectra are undertaken by commercial software, while off-line analysis is carried out by HYPERMET[7].

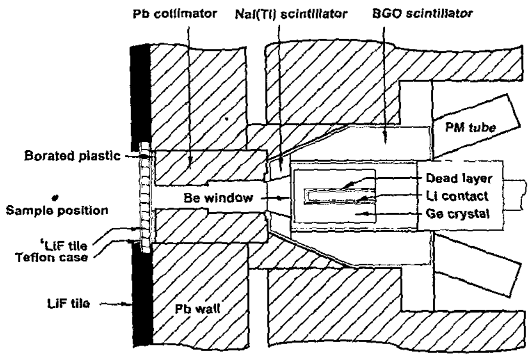

Fig. 1. Schematic Layout of the Multi-mode Assembly of the γ-ray Spectroscopy Detectors

3. Performance

3.1. Characteristics of the Compton Suppression

The spectrum of the germanium detector is characterized by the very prominent continuum, which obscures low-intensity peaks. The Compton continuum in γ-ray spectrum is generated by γ-rays that have undergone one or more scatterings in the detector followed by escape from the detector. The coincident detection of the escaping photons in a surrounding guard detector rejects preferentially those events, which contribute to the continuum, without affecting the full-energy events. The spectra by thermal neutron capture in Fe are shown in Fig. 3. The spectra were measured for 3600 sec in three modes. In the single mode, full energy peaks, together with single-escape (SE) and double-escape (DE) peaks, are registered. In the Compton suppression mode, the Compton continuum is effectively suppressed to about 21% while the full energy peaks are little affected. The Compton suppression factor is about 5 in average in the entire energy region. The single-escape peaks are reduced by a factor of about 5 and double-escape peaks by a factor of about 10 in 6~8 MeV energy region. In the pair mode, only

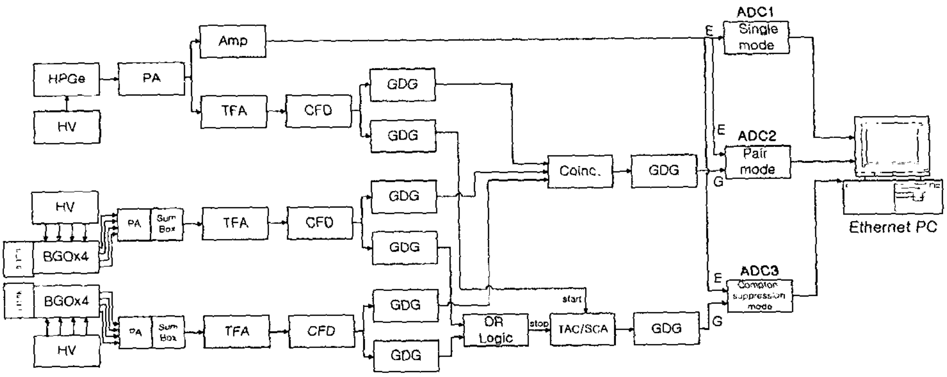

Fig. 2. Block Diagram of the Electronics for the Multi-mode γ-ray Spectrometer Composed of the Single Mode, the Compton Suppression Mode and the Pair Mode. E : energy signal, G : gate signal to ADCs

the escape peaks are registered on flat background distribution, which simplifies the analysis of complex spectra. Peak identification is eased comparing the spectra in the three modes.

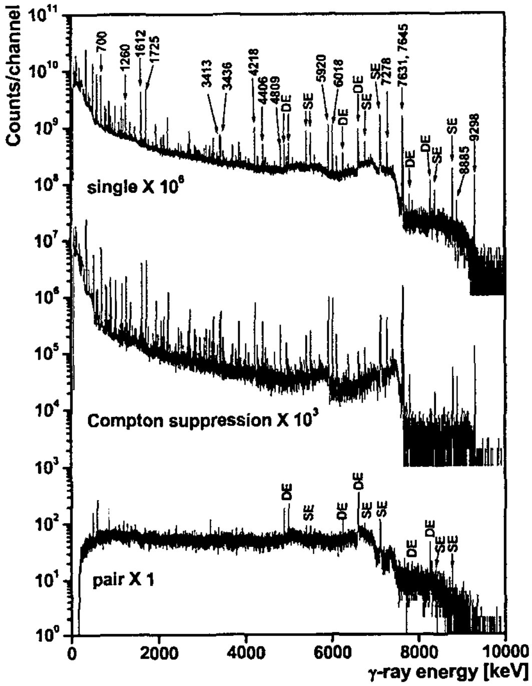

Fig. 3. The Prompt Gamma-ray Spectra of Fe. SE : single escape peak, DE : double escape peak. Live time is 3600 sec

3.2. Efficiency Calibration

The absolute peak efficiency curves of the spectrometer are shown in Fig. 4. The full energy peak efficiency in the Compton suppression mode (after upgrade) is compared with that in the single bare mode (before upgrade). Single- and double-escape peak efficiency curves in the single mode and the pair mode are also shown. The full energy peak efficiency curve of the spectrometer was calibrated by both measuring the standard radioactive sources[8] and measuring the prompt γ-rays from the thermal neutron capture reactions[9]. In the low energy region of 60 keV ~ 1408 keV, ^{60}Co, ^{133}Ba, ^{134}Cs, ^{137}Cs, ^{152}Eu and ^{241}Am were used to generate the absolute full energy peak efficiency curve. The sample for the measurement of the prompt γ-rays was prepared from the mixture of the melamine and ammonium chloride powder. The sample was irradiated in the neutron beam for 80,000 sec. The relative efficiency curves determined for the prompt γ-rays from the $^{14}N(n,\gamma)$ and $^{35}Cl(n,\gamma)$ reactions were normalized to the absolute efficiencies of the low energy range to extend the curve up to 11 MeV. The γ-emission probabilities for the standard radioactive sources were taken from the IAEA-TECDOC-619[10] and those for the prompt γ-rays were taken from the adopted data of the Lawrence Berkeley National Laboratory[11]. The peak efficiency at 1332.5 keV was reduced to about 60% of that before installing the guard detector, which was mainly due to the reduction in the collimator opening. The full energy peak efficiency in the entire energy region was reduced to about 80% of that before upgrade.

All the measured efficiency data were fitted with a 8^{th} order polynomial. Polynomial fit was achieved by weighting the measured efficiency data with the variance of the data, which were determined by propagating the uncertainty of the statistics and that of the γ-emission probability.

The overall uncertainty $\varepsilon(E)$ of the fitted efficiency $\sigma(E)$ for a γ-ray of energy E is given by

$$\sigma(E) = \frac{t(1-\alpha/2, n-k)s\{\varepsilon(E)\}}{1.63}, \quad (1)$$

where t is the student's t-score, α is the level of significance, n is the number of measured efficiency data, k is the number of fitting parameters and s is calculated from[12]

$$s^2\{\varepsilon(E)\} = \left[\sum_{i=1}^{n} \frac{(\varepsilon_i - \bar{\varepsilon})^2}{n-1}\right] \cdot \left[1/n + (E-\bar{E})^2 / \sum_{i=1}^{n}(E_i - \bar{E})^2\right], (2)$$

where $\bar{\varepsilon}$ and $\bar{E}$ is the mean efficiency for the measured efficiency and the mean energy for the γ-ray energy data, respectively. α is taken as 5% and k is given as 9 since the 8^{th} order polynomial of γ-ray energy is used in the fitting. The 1σ-uncertainty is less than 1% in the energy region of 0.3 ~ 6 MeV and remains less than 2% in the other energy region. In comparison with the efficiency calibration performed before upgrade[6], the present calibration reduced the efficiency uncertainties by a factor of about 2~3.

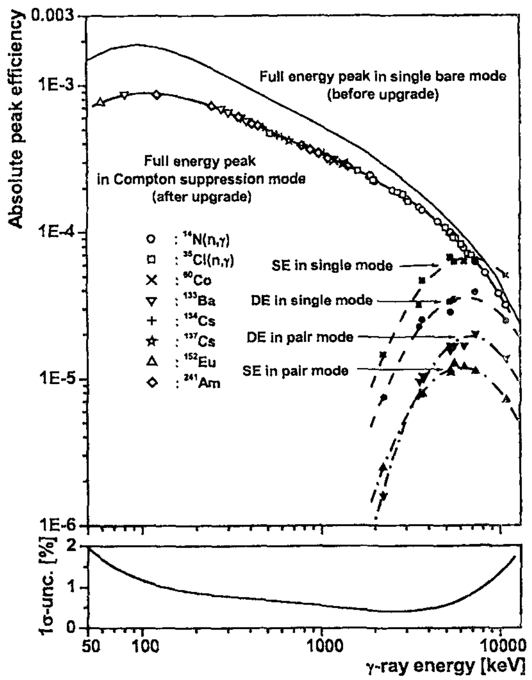

Fig. 4. Absolute Peak Efficiency Curves of the γ-ray Spectrometer. Full Energy Peak Efficiency in the Single Bare Mode (before upgrade) and in the Compton Suppression Mode (after upgrade). The Single- and Double-escape Peak Efficiency Curves in the Single Mode and the Pair Mode. SE : single escape peak; DE : double escape peak. The 1σ-uncertainty of the Full Energy Peak Efficiency in Compton Suppression Mode is Shown in the Bottom

3.3. Channel-energy Non-linearity Calibration

Even though the HPGe detector allows a fairly accurate determination of the peak position, the non-linearity in the spectrometer may lead to erroneous energy readings and hence a wrong isotopic identification, unless a precise channel-energy non-linearity calibration is included. The non-linearity is usually defined as the deviation of the measured peak position from the peak position of a linear calibration determined by the accurately known γ-ray energies based on the standard radioactive sources or the prompt γ-rays emitted from neutron capture. The detailed calibration procedure adopted the prescribed method in Ref. [13]. The γ-rays from ^{134}Cs and ^{152}Eu and the prompt γ-rays from neutron capture in nitrogen and chlorine were used. The measured non-linearity data were fitted with a 6^{th} order polynomial by weighting the measured non-linearity data with the variances, which were determined by propagating the uncertainty of the measured peak position and that of the calibration γ-ray energies. The uncertainty of the non-linearity

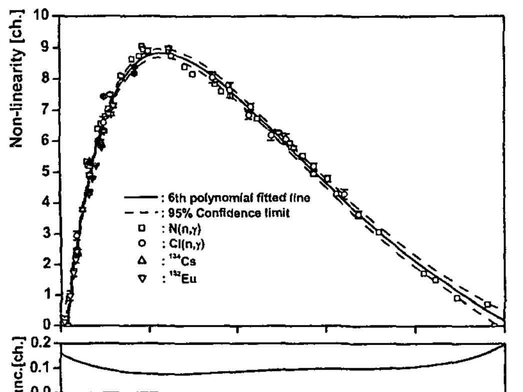

Fig. 5. Non-linearity Data Measured Using ^{134}Cs, ^{152}Eu and Prompt γ-rays from Neutron Capture in Nitrogen and Chlorine and Its 1σ-uncertainty Data

function was assigned similarly as in the calculation of the uncertainty of the efficiency function. The non-linearity and its 1σ-uncertainty are shown in Fig. 5. If the non-linearity calibration is periodically performed, the γ-ray energy can be determined with a precision of below 0.2 channels.

3.4. Background

The minimum detectable activity in the sample is largely dependent on the magnitude of the background of the γ-ray spectrometer. Hence the background level must be reduced as low as possible. For the arrangement including the installation of the BGO/NaI(Tl) guard detector, the total background count rate was reduced to a level of about 250 cps, which is about 1/10 of that before upgrade. Fig. 6. shows the γ-ray backgrounds measured for 200,000 sec in air environment. The important background peaks in the single mode and the Compton suppression mode are identified and compared with those before upgrade[14] in Table. 2. The most intense peak in the Compton suppression spectrum is the 75 keV Pb K_α X-ray peak with a count rate of 3.74 cps. A portion of the background spectrum in 500 ~ 1300 keV region is shown in Fig. 7 to indicate the characteristic background peaks of the prompt γ-ray spectrum. The most of the identified lines result from the neutron capture and inelastic scattering by the five stable germanium isotopes. The representative inelastic scattering peaks, which form the triangular shapes, are located at 1039.6 keV position resulting from $^{70}Ge(n,n'\gamma)$, at 694.0 keV position from $^{72}Ge(n,n'e^-)$, at 834.0 keV position from $^{72}Ge(n,n'\gamma)$, at 596.0 keV and at 1204.1 keV positions from $^{72}Ge(n,n'\gamma)$ and at 562.9 keV position from $^{76}Ge(n,n'\gamma)$[15]. These are used as monitor of fast neutrons incident on the germanium crystal. The relation between 694.0 keV inelastic scattering peak count rate (C_p) in cps, the effective detector volume (V) in cm^3 and fast neutron flux (ϕ_f) in n/cm^2s is given by

$$\phi_f = 300\frac{C_p}{V}. \quad (3)$$

The fast neutron flux (ϕ_f) incident on the germanium crystal is estimated to be 2.8 n/cm^2s, about 60% of that before installation of the guard detector[14]. The estimated rate of the fast neutron irradiation insures the detector performance against radiation damage for a running period over 10 years. The thermal neutron capture peaks, which are prominent in the single mode, are effectively suppressed in Compton suppression mode but the triangular inelastic scattering peaks are little suppressed. Table 3 compares the reported background count rates of the various existing facilities.

Radiation levels at the position of 20 cm from

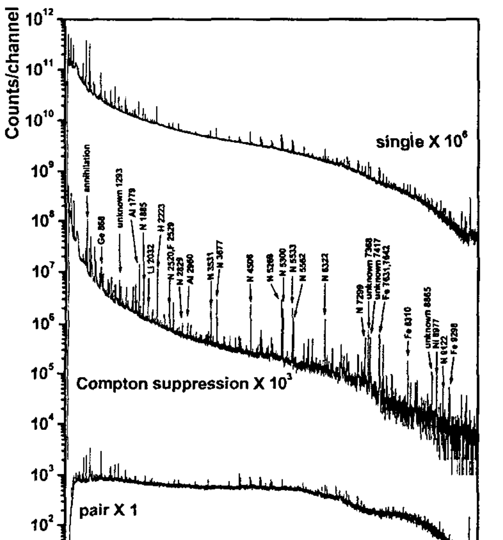

Fig. 6. Comparison of the γ-ray Background Spectrum in the Single Mode, the Compton Suppression Mode and the Pair Mode

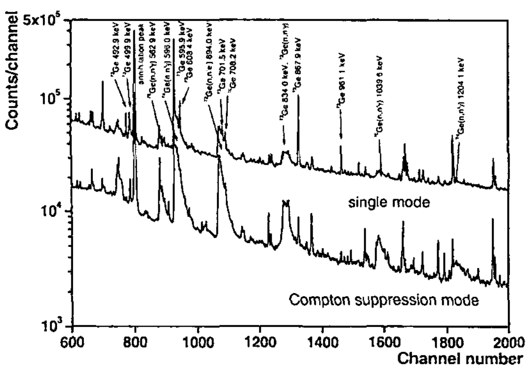

Fig. 7. The Background γ-ray Peaks Induced by the Ge(n,γ), Ge(n,n′γ) and Ge(n,n′e⁻)

the lead wall were kept low to ensure safety. The measured γ-ray and neutron dose rates were 10 $\mu Sv\ h^{-1}$ and 30 $\mu Sv\ h^{-1}$, respectively.

4. Conclusions

The γ-ray detection system of the SNU-KAERI PGAA facility was upgraded recently to multi-mode γ-ray spectrometer, which includes the single mode, the Compton suppression mode and the pair mode by adding a BGO/NaI(Tl) guard detector and associated electronics. The performance of the Compton suppression mode was tested by using the prompt γ-rays from Fe by neutron capture. The averaged Compton suppression factor in the entire energy region is about 5. The full energy peak efficiency determined in the Compton suppression mode is reduced in average to about 80% of that before upgrade. The background count rate was,

Table 2. Background Peak Count Rates (in cps) Under Neutron Beam Irradiation with no Target

Energy [keV]	Element or nuclide	Before upgrade [14]	After upgrade	
		Single bare HPGe	Single mode	Compton suppression mode
	Total count rate	2912	682	253
75	Pb K_α X	54.2	3.73	3.74 ±0.06
85	Pb K_β X	17.8	0.65	0.64 ±0.02
175	^{70}Ge(n,γ)	4.9	0.40	0.26 ±0.01
198	Unknown	16.8	1.87	0.09 ±0.02
254	^{74}Ge(n,γ)	2.9	0.24	0.08 ±0.03
478	^{10}B(n,αγ)	-	0.34	0.33 ±0.01
500	^{70}Ge(n,γ)	2.9	0.21	0.13 ±0.01
511	Annihilation	23.6	2.46	2.37 ±0.03
596	^{73}Ge(n,γ)	10.2	5.53	1.25 ±0.06
708	^{70}Ge(n,γ)	1.22	0.52	<0.01
868	^{73}Ge(n,γ)	2.68	1.76	0.03±0.005
1294	Unknown	4.03	0.23	0.08±0.006
1460	^{40}K decay	1.31	0.04	0.04±0.001
1779	^{28}Al decay	0.46	0.28	0.27±0.002
1885	N(n,γ)	0.41	0.18	0.18±0.002
2223	H(n,γ)	0.80	0.26	0.24±0.002
7368	Pb(n,γ)	0.36	0.03	0.03±0.001
10829	N(n,γ)	0.03	0.01	0.01±0.001

Table 3. Background Peak Count Rates (in cps) Under Neutron Irradiation Between Facilities

Element	E([keV]	Univ. Md-NIST [16]	University of Missouri [16]	JAERI [17]		Present Study
				Cold	Thermal	
H	2223	1.56	0.51	0.0094	0.0019	0.24±0.002
Li	2033					0.01±0.001
B	478	0.1	<0.1	<0.004	<0.0021	0.33±0.01
C	1262	0.0014	0.035	0.002	<0.0007	0.01±0.002
N	1885	0.072	<0.008	0.0025	<0.0012	0.18±0.002
F	2529					0.01±0.002
Ar	167					0.11±0.01
Na	472	0.057	0.349	<0.0035	<0.0012	0.12±0.01
Al	3034					0.27±0.001
Si	3539					<0.01
Cl	517	0.007	0.009	<0.0019	0.0012	
Ti	342		0.063	<0.0025	<0.0016	
Cr	835					0.02±0.002
Fe	1725	0.007	0.136			0.03±0.002
Co*	1332					0.05±0.002
Ni	465					0.02±0.01
Cu	278					0.1±0.02
Zn	1077					<0.01
Ge	868					0.03±0.004
Sn	1229					<0.01
I	421					0.03±0.003
Pb	7368					0.03±0.0001
^{207}Bi	569			0.0242	0.0327	0.02±0.01
^{207}Bi	1063			0.0081	0.0097	0.01±0.001

* delayed γ-ray

however, largely diminished at the expense of a small reduction of the detection efficiency. The total background count rate was reduced to a level of 250 cps, which was about 1/10 of that before upgrade. Hence, the background reduction and the Compton suppression technique provided the spectrometer with the enhanced performance. The detection limits and the uncertainty of efficiency were greatly improved through the upgrade work.

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