Chapter II

Experimental set-up, procedure and Monte Carlo methods

2.1 Introduction

The experimental set-up and the theoretical methods used for this study are described in this chapter. The details regarding the automation of the instrument, data acquisition and analysis of scattered intensity are discussed. Monte Carlo N Particle (MCNP) \cite{1} code is utilized in this work as a supportive tool for the experimental studies. The important functions of MCNP employed in the simulations are described. In the scattering experiments, intersection of source and detector field of view is known as voxel and it decides the spatial resolution of the technique. When diverging source and detector beams are considered, the intersection of two cones inclined at an angle is the resultant voxel. The analytical method followed for calculating the voxel size is also described in this chapter.

2.2 Experimental set-up

The experimental set-up used for this study is an indigenously designed automated PC controlled scanning system consisting of CNC controlled 6-axis source detector system and 4-axis job positioning system, a High Purity Germanium (HPGe) detector and radioactive sources ($^{137}$Cs and $^{241}$Am). The schematic diagram and photograph of the experimental set-up are shown in figures 2.1 and 2.2 respectively. Shielded sources and
detector, sample holder and the job positioning system for the movement of sample are marked in the photograph (figure 2.2). This set-up can be used for scattering and transmission experiments simultaneously. The details of the various components of experimental set-up are described below.

\[\text{Figure 2.1 Schematic of the experimental set-up}\]

\[\text{Figure 2.2 Experimental set-up}\]
2.2.1 Radioactive sources

The first step in photon transmission or scattering processes is photon incidence on target material. For this purpose a ‘photon source’ is required which can provide high intense and well defined energy photons. Generally X-ray systems are used as the source for photons in which energy will be in the range of few keV. The penetration power of X-rays is less compared to that of gamma rays. Thus the sample thickness that can be analyzed or the scanning depth is limited by this fact. Bremsstrahlung photon beams (3-6 MeV) from small electron Linear Accelerator (LINAC) is used for greater penetrability and high intensity. These unique features make it a very desirable photon source for industrial applications. However, the installation and maintenance cost of LINAC system makes it less preferable. Radioactive sources are other choice for gamma photons. The gamma rays from radioactive isotopes produce an energy spectrum that has distinct emission energy peaks, thus providing well-defined photon energies that enable easier analysis of the measured signal. Moreover, gamma ray isotopic sources are portable, self-contained, self-energizing, small in size and usable in hostile environments. The other advantages of these radioactive sources are relatively long half-life, high specific activity and simple means of production. The disadvantage of using the radioactive isotopes is the low counting rate compared to the high counting rate of X-rays and LINAC. It is preferable and very convenient to use $^{137}$Cs radioactive source which emits photons of energy 661.6 keV, within the energy range where the Compton process dominates. The $^{60}$Co (1.17 and 1.33 MeV) can also be used for higher penetration but it is desirable to use radioisotopes that emit mostly at a single energy. Otherwise, detector may not be able to distinguish between scattered energies of the original
photons with energies very close to each other. This will result in ambiguity and
complexness in the variation of count rate with energy and density.

$^{137}$Cs radio isotope which emits gamma photon of 661.6 keV is a fission product and
it decays by beta mode to $^{137}$Ba with a half life of 30.2 years. The decay scheme of the $^{137}$Cs
is depicted below in figure 2.3 and sources of activity 4.2 Ci and 4.3 mCi are employed for
scattering and transmission experiments respectively. This particular source is selected
because of its mono energetic nature, long half-life and due to the predominant cross section
for Compton process in its energy range. Comparably lower strength source is used for
transmission experiments to reduce the continuum background in scattered Pulse Height
Spectra (PHS) when transmission and scattering experiments are performed simultaneously.

\[ \begin{array}{c}
\text{Cs}^{137} & \text{Ba}^{137} \\
1.17 \text{MeV} & 0 \text{MeV} \\
5.6\% & 85\% \\
1.176 \text{MeV} & \gamma \\
0.511 \text{MeV} & 94.4\% \\
\beta^- \\
\end{array} \]

\text{Figure 2.3 Decay scheme of }^{137}\text{Cs}

$^{241}$Am isotope decays by alpha decay to $^{237}$Np with a half-life of 432.7 years and the
predominant gamma energy following the alpha decay is 59.54 keV. This isotope has found
applications in many commercial uses including fluid density gauges, thickness gauges and
medical diagnostic devices and a 10 mCi source is used for conducting the transmission experiment. Due to the low penetration capability of 59.54 keV gamma photons from $^{241}$Am, its usage is limited for high dense, thick or hidden inside high density background materials. The decay scheme of $^{241}$Am source is shown in figure 2.4

![Decay scheme of $^{241}$Am](image)

**Figure 2.4 Decay scheme of $^{241}$Am**

### 2.2.2 Detector and electronics

A pulse height analysis system includes the detector and the corresponding processing electronics units. The block diagram of the detector system along with other electronic components is shown in figure 2.5. A detail description about each of these components is provided.

![Block diagram of detector system with electronics](image)

**Figure 2.5 Block diagram of detector system with electronics**
2.2.2.1 Detector

Commonly used radiation detectors are ionization chambers, proportional counters, Geiger Muller (GM) counters, scintillation detectors and semiconductor detectors. Ionization detectors are the first electrical devices used for detecting radiation \(^2\). Ionization produced by charged particles is the basis of detection in ionization chamber, proportional counter and GM counter and the efficiency of detection for gamma rays is relatively poor. Detection of radiation based on the scintillation produced by them in crystals like NaI is the working principle of scintillation detectors. Electron-hole pair generation due to the ionizing radiation in a depleted layer of p-n junction semiconductor is utilized for the detection of radiation in semiconductor detectors. Energy required for producing an e-h pair is 2.96 and 3.62 eV for Ge and Si respectively which is very small compared to the 100 eV for photoelectron generation in scintillation counter and 30 eV for ion pairs in gas chamber \(^3\). More e-h pairs are produced for the incident energy in semiconductor detectors and hence high resolution is achieved compared to scintillation detectors. Energy resolution is the ability of a detector to detect and differentiate two closely lying energies and it is nearly 0.15% and 6% for HPGe and NaI detectors respectively at 1.33 MeV gamma energy. High resolution is a requisite for detectors employed in Compton scattering applications and this reduces the multiple scatter contribution in the scattered Pulse Height Spectra (PHS).

A 50% efficiency high resolution Bruker Baltic make HPGe p-type co-axial detector is used in the present experiment. A liquid nitrogen dewar vessel of capacity 30 L is attached to the detector. Gamma ray energy range of this detector is 40-10000 keV. All cooled parts of the detector unit are covered with multi layer thermal insulation in order to reduce the heat leakage. The cross sectional image of the crystal is given in figure 2.6. The crystal size of
detector is 6.6 cm in diameter and 6.6 cm in length and the end cap is of thickness 0.6 mm. The detector resolution at 661.6 keV is found to be 0.21%.

**Figure 2.6 Cross sectional image of 50% efficiency detector**

### 2.2.2.2 Preamplifier

A preamplifier is integrally attached to the detector as close as possible and the main function of preamplifier is to provide impedance match between the high impedance of the detector with the low impedance of the amplifier. In addition to this, bias voltage is applied to the detector through the preamplifier. Preamplifiers can be of charge sensitive or voltage sensitive type and in voltage sensitive configuration, the amplitude of the output pulse will be proportional to the amplitude of the input pulse. But for semiconductor detectors charge sensitive preamplifiers are used and in this configuration the output voltage is proportional to the integrated charge supplied to the input terminals. The incoming charge is collected in a capacitor and discharged through a resistance feedback network. This makes the output of
preamplifier a linear tail pulse with large decay time and help to facilitate the full collection of charge from detectors. In the present experimental set-up, detector and input stage of preamplifier are placed inside the vacuum chamber and cooled to liquid nitrogen temperature. Warm part of preamplifier is placed outside of the chamber with connecting wires. The low voltage +/- 12 V is fed to preamplifier/ detector during operation. The preamplifier used is having an output signal voltage rise time less than 0.15 μs and output signal voltage fall time less than 50 μs.

2.2.2.3 High Voltage (HV) power supply

Most of the radiation detectors require an external voltage supply known as detector bias for proper detection. Ionization chambers require low biasing voltage whereas semiconductor and scintillation detectors require bias voltage in the order of kV. The bias voltage for optimum resolution for the HPGe detector used in the present work is + 4500 V and this is provided from a programmable HV power supply which can provide +/- 5500 V maximum output accommodated in a Nuclear Instrumentation Module (NIM) bin of CAEN make. HV outputs are delivered through SHV connectors. The output polarity is selectable and the selected polarity will be indicated by two LEDs on the front panel. A provision for the ramping step size (RAMP-UP and RAMP-DOWN) selection is available. Safety features available in this HV model are over voltage and under voltage warning when the output voltage differs from the programmed value by more than 2%, a provision for setting maximum voltage to avoid the over biasing of detector and over current detection. When the over current status is lasting more than the pre set time, the output voltage will become zero either in the RAMP-DOWN rate or at the fastest rate.
2.2.2.4 Spectroscopy amplifier

The signal produced in detector is too small to be processed without amplification. The output signal from pre amplifier is connected to an amplifier for proper amplification of the signal. Generally the input of the amplifier is a tail pulse with a decay time of approximately 100 μs, and if another pulse is also coming within this period, the amplitude will increase and this is known as pile up. To avoid pile up either counter rate has to be decreased or a proper pulse shaping has to be provided. The spectroscopy amplifier also provides pulse shaping to prevent the pulse pile up and to optimize signal to noise ratio. A direct relationship between input and output amplitudes is required for obtaining pulse height information and a linear amplifier is used to preserve the same. In the present experimental set-up, a linear amplifier of Tennelec make with selectable peaking times of 1, 2, 4, 8, 16 and 24 μs is used. A peaking time of 4 μs is utilized for the present experiments. Gain range is a continuous variable from x 2.5 to x 3000 through coarse gain and fine gain adjustments. Coarse gain is facilitated through nine position rotary switch (5 to 2000 in a 1-2-5 sequence) and fine gain is facilitated by a ten turn precision potentiometer with linear calibration from 500 to 1500 in multipliers of 0.5 and 1.5. Provision for pole zero baseline correction is available in this amplifier through an adjustable P/Z control.

2.2.2.5 Multi-Channel Analyzer (MCA)

The linear amplifier output is fed to a Multi-Channel Analyzer (MCA) for further processing and it provides a visual display of the spectrum. When MCA operates in pulse height analyzer mode, the input pulses are sort out into channels according to the amplitude. A Single Channel Analyzer (SCA) counts the pulses between a lower limit and upper limit defined by the user. MCA can be considered as an array of SCAs with different lower and
upper limits. Thus MCA covers the whole voltage range at the same time. In MCA the amplitude of the analog signal from linear amplifier is converted to corresponding digital signals with the help of an Analog to Digital Converter (ADC) and this digital value is used as the address of a memory location which will increment according to the pulse amplitude.

In nuclear spectroscopic systems, ADCs converts the analog signal to digital signal according to their peak value. Therefore, this ADC is known as peak sensing ADC. Most of the ADCs used for spectroscopy system is meant to work in the span of 0 to 10 V. The conversion gain of the ADC mentions the total number of channels available. The conversion is achieved with the help of a comparator where one of the inputs will be the analog signal to be converted. A constantly increasing ramp signal is applied to the other input of the terminal and when the ramp voltage becomes larger than the signal, corresponding digital value of the ramp is provided as the digital output. Another type of ADC which uses mainly for spectroscopy applications is Wilkinson type ADC, where a capacitor is charged using the input voltage. Then the capacitor discharges and a scaler counting from a constant frequency clock is gated on at the start of capacitor discharge. When the capacitor discharges fully, the scaler gate is put off and the contents in the scaler will be proportional to the charge on the capacitor. This method is more linear than other conversion methods and hence preferred for spectroscopy work. MCA sort out incoming pulses according to the pulse height of the analog signal with the help of an ADC and record the count at each pulse height in a memory. The value in each of this memory channel will increment corresponding to the digital value from ADC. The gamma spectroscopic data acquisition is done by FAST COM 8K MCA PC add-on card. It includes a built-in pulse height analyzing Wilkinson type ADC with 500 ns conversion time and 8 k conversion range i.e., 10 V pulse will be stored in 8192\textsuperscript{th}
channel. The present system provides 8192 channels and the number of counts corresponding to each channel i.e., pulse height spectra is displayed. The features are high-resolution graphics displays with zoom, linear and logarithmic (auto) scaling, grids, region of interests, Gaussian fit, calibration using diverse formulas and FWHM calculations.

2.2.3 Shielding

The source and detectors are well shielded to ensure the minimum background radiation and to increase the signal to noise ratio in the detector resulting in improved sensitivity. The sources employed in scattering and transmission experiments are shielded using 160 and 100 mm thick lead cylindrical structures respectively and the detector with 50 mm thick lead shield. The lead shields are lined and enclosed in stainless steel sheets of thickness 5 mm.

2.2.4 Collimators

In the present study, well collimated source and detector systems are employed. In scattering experiment, collimating the source and detector help to obtain the information from an elemental volume determined by the intersection of source and detector beams known as voxel. Multiple scattered photons affect the signal-to-noise ratio and reduce the contrast and sensitivity and can be minimized by introducing a ‘hard collimation’ or collimators. In transmission experiments collimators are used to obtain narrow parallel beam geometry and to avoid the buildup factors. Cylindrical lead collimators of various sizes and opening diameters (7 mm and 5 mm) are used in the present experiment to achieve the best results in each case studied.
2.2.4.1 Voxel size calculation

In a gamma scattering experiment, the size of the voxel determines the spatial resolution of the system. When smaller diameter source and detector collimators are used with a reduced distance to sample position small voxel size can be achieved. As the distance between source to sample and sample to detector increases, divergence of beam also increases and this results in the increase of the voxel size. An accurate calculation of voxel size is needed for proper interpretation of the result. Similarly during the design of a system, or during the selection of proper collimators or source detector locations, an idea about the voxel size is unavoidable. Since the source beam and detector point of view are divergent in nature, voxel size can be calculated from determining the intersection volume of two cones. The voxel size is calculated using the method described by Balogun [4,5] from the information of scattering angle, collimator length, diameter and distance between the sample to source and sample to detector.

![Geometry used for calculating the voxel size.](image)

Figure 2.7 Geometry used for calculating the voxel size.
The voxel size is calculated using analytical and Monte Carlo methods. The geometry used for calculating the voxel size is shown in figure 2.7 and the scattering angle $\theta$, divergence of source and detector beams $\alpha$ and $\beta$ respectively are marked in the same figure. The parameters $\alpha$ and $\beta$ are calculated from the collimators length and radius. The equations of four straight lines ($l_1$, $l_2$, $l_3$ and $l_4$) can be obtained from $\alpha$ and $\beta$ and the intersections of any two pair of these lines define the corners (P, Q, R, S) of the voxel. In analytical method a sequential scanning of an elemental volume of known size across the volume defined by the region PQRS is carried out. Whenever the elemental volume is inside the voxel defined by the corners (P, Q, R, S), a counter is increased. Finally the total volume is calculated as the product of counter and the elemental volume.

![Figure 2.8 Calculated voxel sizes for different collimator combinations (source diameter x detector diameter) as a function of scattering angle.](image-url)
The size of the voxel for various collimators and scattering angles are calculated. Figure 2.8 shows calculated voxel sizes as a function of scattering angle for various source detector collimator combinations. It can be seen that voxel size is minimum at 90° and remains almost same in the angular range 60 to 120° and all the experiments are carried out in this angular range. It is observed that a smaller voxel size resulting in improved spatial resolution can be achieved by incorporation of 3 mm collimators for source and detector. But relatively higher scanning times are needed to achieve even a 2% statistical uncertainty in scattered intensity and it demands a compromise between scanning time and achievable spatial resolution. Hence a 7x7 combination (i.e., 7 mm collimators for both source and detector) is selected only when bulk properties are to be determined. A 5x7 source-detector collimator combination is used for obtaining desired improved resolution in some of the experiments. All the collimators selected are of length 8 cm. The voxel size comparable to that obtained by using 3 mm collimators either on source or detector can be achieved by selecting a 7 mm diameter and 14 cm length collimator (7x7(l)) with less divergence at detector end as seen in figure 2.8. This combination of collimators is used for three dimensional imaging experiments which demanded a higher accuracy.

When the sample size is much smaller compared to voxel selected for investigation, a condition which describes the geometry of the sample is also incorporated to the above method. The condition imposed is that the scattering volume is considered only when the elemental volume is inside the intersection of two cones as well as the geometry of the sample defined.
2.3 Experimental procedure

The scattering experimental set-up consists of CNC controlled 6-axis source detector system and a 4-axis job positioning system. The source and detector are mounted separately on the source and detector sub assemblies of 6-axis system. The motion of the specimen disk is derived by 4 servo motors. Three motors are used to move it in three mutually perpendicular Cartesian coordinate system denoted X, Y, Z. One more servo motor used to rotate it and this coordinate is denoted as W. The servo motors are controlled by Galil’s DMC 2040 motion controller programmed with Galil commands and the commands are communicated from PC via high speed RS 232 port. The DMC controller will send the pulses to servo motors. In the present system each pulse will move along X, Y, Z-axes linearly by 1 micrometer and each pulse corresponds to 0.0004° rotation in the W axis. The servo driver receives the input signals from the controller system for generating motion in servomotors by transmitting the electrical signal according to the signals from the controller. The controller system can be programmed by the user as per the required motion. The controller is programmed by the binary or ASCII Galil Commands. The positional accuracy of source and detector system is ± 50 μm for X and Z-axis travel stages and for 4-axis job positioning system it is ± 10 μm for X, Y and Z-axis travel stages. The positional accuracy for θ rotary stages for both the systems is ± 0.25°.

The scattering source and detector positions can be moved using the user input commands. An optical method using laser pointer is used to ensure the alignment and to locate the scattering position. The sample holder is at a distance of 93.4 cm and 52.1 cm from the source and the detector surfaces respectively. A test specimen is placed in the centre of the scattering position and the scattered intensity is recorded. An exact scattering location is
zeroed on by moving the test specimen around the scattering position and this corresponds to the maximum intensity point. In similar way transmission source and detector positions are optically aligned and the sample holder position is fixed as described earlier. The sequence of sample movement and data recording are automated and synchronized and is described in detail in the next section.

2.3.1 Automation details

Three dimensional scanning of the objects are obtained using a raster movement of sample along the lateral, horizontal and vertical directions. To achieve fast and effective voxel by voxel scanning, it is required to have a synchronized data collection and automatic translation of the sample (or detector and source system). In the present work, the translation, rotation and vertical motions of 4-axis CNC controlled job position system and MCA data acquisition are fully automated and synchronized using VB based windows application program. The block diagram of the components used for automation and synchronization of sample movement and data collection is shown in figure 2.9.

![Figure 2.9 Block diagram of automation and data collection](image-url)
The data acquisition, parameter setting of the MCA and the 4-axis motion are automated using dynamic link library and Galil Active-x tool files. The PC first send the signal to DMC to reset the position by energizing the servo motors and then it will direct the MCA to collect the data in preset live time. Many different tasks can be executed by simple commands such as initialization, position sensing, repositioning the scanner, start and stop a measurement, store the accumulated data on disk and automatically execute all steps for a complete sequential scanning. The collected counts in the specified energy region are stored in the output file of PC. The output file contains parameters of collection time, scanning period, X, Y and Z positions, gross and net photopeak counts for the given region of interest. Figure 2.10 shows the images of control panel (top) and automation screens (bottom).

![Image of control panel and data collection screen](image)

**Figure 2.10 Images of control panel and data collection screen**

### 2.3.2 Data analysis

Scattering and transmission PHS are collected simultaneously and appropriate corrections are applied for continuum and background counts. Figure 2.11 is a typical PHS
showing scattered and transmitted photo peaks at 252 and at 661.6 keV respectively. A background spectrum is collected with bare sample holder without any sample in its position and the same is subtracted from all the spectra for further analysis.

Figure 2.11 PHS of scattered (252 keV) and transmitted (661 keV) intensities

Figure 2.12 Continuum subtraction for photopeak
The area under the photopeak is used for further analysis. But the scattered photopeak is affected by the Compton continuum of transmitted intensity and hence a proper correction is required and this is carried out as follows \(^3\). The integrated counts under the photo peak for \(n\) channels are calculated as \(C_i\) as indicated in figure 2.12. A constant Compton continuum contribution to the photo peak is assumed in the present case and taken into account. The counts to be subtracted from photo peak are obtained by calculating the average continuum count per channel from the gross count of \(m\) channels \(C_a\) and \(C_b\) as indicated in the figure 2.12. The corrected photo peak count \(C\) is calculated using the following formula:

\[
C = C_i - n \left( \frac{C_a + C_b}{2m} \right)
\]

\((2.1)\)

### 2.4 MCNP

The Monte Carlo simulations have been done to provide support of the experiment. The simulation takes into account the detailed known characteristics of the source, detector and the scatterer, in calculating the PHS. The MCNP4C \(^1\) radiation transport code developed by Los Alamos National Laboratory, USA is applied to perform the calculations in this work and it is a general purpose, three-dimensional general geometry, time-dependent code, which is used to calculate coupled neutron-photon-electron transport in bulk media. For photons, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung. MCNP provides a nearly predictive capability of how radiation interacts with matter. In MCNP simulations, each particle (photon) is tracked from creation to termination with all interactions based on physics models and cross-sections, and all decisions (location of interaction, scattering angle, etc.) are based on pseudo-random
numbers. Usually, the results of a simulation are normalized per starting source photon. New source photons are randomly created until a preset number of histories are tracked and the simulation is ended. The MCNP code is very effective in obtaining a simulated spectra produced by gamma rays in a detector provided the experimental set-up can be modeled accurately.

2.4.1 Detector, source model

A detailed three dimensional geometry consisting of well collimated and shielded source and detector assemblies and the object is modeled with exact dimension, distance and orientation. Two $^{137}$Cs radioactive source capsules each of activity 77.7 GBq (total 155.4 GBq) deposited inside stainless steel and the HPGe detector is modeled with the surrounding lead shielding and a 0.007 m beam collimator for both source and detector. The HPGe detector consists of a crystal of size 0.066 m × 0.066 m surrounded and sealed by an aluminum layer of 0.002 m thick in front and 0.001 m on sides. Sample dimensions and their distances from the collimator edge of source and detector set-up, the scattering angle and the sizes of the source and detector collimators are incorporated in the modeling. Any small deviation in the geometrical parameters of the entire set-up may lead to inaccuracy in the simulated spectra. Hence great care has been taken while measuring the distances, angle etc. For modeling the source and detector, the cross sectional diagrams given by the supplier/manufacturer have been referred.

2.4.2 Pulse Height Spectra (PHS) simulation

The simulated PHS can be compared with the experimental ones to support the experiment and confirm the results. The PHS in MCNP is the distribution of the energy deposited in a “cell”, i.e., the gamma ray energy spectrum in a physical model of a detector.
**F8 tally:** F8 tally of MCNP is employed to obtain the simulated PHS and it is analogous to physical detector. The estimation is based on the following approach. When a photon enters the cell, the cell is credited with energy \((E_{\text{in}})\) times the weight \((\omega)\) of the incoming photon. If the photon leaves the cell, the product of Energy \((E_{\text{out}})\) and weight \((\omega)\) is deducted from the cell energy.

\[
E_{\text{cell}} = \sum_{\text{tracks}} (E_{\text{in}} \omega - E_{\text{out}} \omega)
\]  

(2.2)

At the end of each history, the energy in each cell is divided by the source weight. Hence for each history, only one count is added to the spectrum. The pulse height tally is used to obtain the energy distribution of pulses created in the volume of the germanium crystal. The F8 energy bins correspond to the total energy deposited in a detector in the specified channels by each physical particle.

**GEB card:** Gaussian broadening is provided to the spectra by MCNP function called ‘GEB card’ and hence a good representation of the experimental spectra is achieved. The constants \(a\), \(b\) and \(c\) take care the broadening and they are obtained from

\[
\text{FWHM (MeV)} = a + b\sqrt{(E + cE^2)}
\]

(2.3)

where \(E\) is the energy in MeV. Scattering experiments are performed at three different angles using the same set of source and detector collimators and the corresponding FWHM and scattered energy values are used to obtain the constants \(a\), \(b\) and \(c\).

**Source biasing:** For the pulse-height estimates used in this study, the source biasing represents the only feasible method to improve computational efficiency. Source is adjusted to emit into a restricted solid angle depending upon the collimator size, and thus to avoid unneeded calculations.
**Binning and comparison:** The simulated pulse height spectra contain 28 bins each with 3.615 keV width and the photon energies ranged from 198 to 303 keV. The experimental spectrum is rebinned to the same energy grid as of MCNP for comparison. Each simulation is run with $2.1 \times 10^9$ source particles for decreasing the relative variance. Each value of simulated spectra is multiplied by source activity and acquisition time to make the simulated spectra directly comparable with the background subtracted experimental PHS.

**References**