# Investigating prompt gamma emission for a Carbon target using AFRODITE clover detectors

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**Abstract.** Over the last few decades remarkable progress has been made in radiotherapy treatment modalities towards effectively delivering a radiation dose to the planning target volume (PTV) while increasing the survival and reducing the side effects of cancer patients. Proton therapy has become an increasingly popular treatment modality due to its superior dose distribution. However, the advantage of proton beams cannot be fully utilized since no proper method is currently available to measure in-patient proton dose. The detection of secondary prompt gamma rays have been proposed as an in-situ method to determine the proton range since the location of the prompt gamma emission is strongly correlated with the proton depth dose profile. Previous work, using Monte Carlo simulations, has shown discrepancies with the production of prompt gamma data particularly in prominent elements found in tissue within the therapeutic range (50-250 MeV). The goal of this study is to investigate (using simulations and measurements) the prompt gamma emission for the element of carbon. Measurements using a thin target of natural Carbon at the energy 95 MeV were performed at iThemba LABS using the AFRODITE detector system. The experimental setup was then simulated using the Geant4 Monte Carlo toolkit and the results were compared to the measurements.

## 1. Introduction

The foremost goal of radiation therapy is precise targeting of the tumour volume with minimal exposure to surrounding normal healthy tissues. Proton therapy takes advantage of the steep dose fall-off at the end of the range of the protons in tissue, resulting in a significant reduction in dose to the organs at risk and precise dose conformity while increasing tumour control probability. However, the location of the distal fall-off (Bragg peak) is an uncertain parameter due to the various uncertainties in the treatment delivery.

In radiotherapy, sources of uncertainty are a recognized concern and are addressed by increasing the size of the treatment margins. While there are many possible uncertainties (organ motion, set-up errors, imaging artifacts) [1], the most critical factor in proton therapy treatment is precisely knowing the range of the proton beam, allowing for more exact dose delivery. A dislocation of the Bragg peak due to these uncertainties can lead to either under-dosage or over-dosage in the treatment delivery. Therefore, in order to fully utilize the advantage of a proton therapy treatment beam it is important to verify the location of the Bragg peak. Due to the fact that treatment protons stop within the patient, secondary prompt gammas have been proposed as a technique for range verification. Although it has been shown that prompt gamma emission is well correlated with the proton Bragg peak [2, 3], Monte Carlo simulations have not been able to accurately reproduce the spectra for prompt gamma spectra produced by carbon [4, 5, 6]. Therefore, this study investigates the prompt gamma spectra from carbon using the AFRODITE (AFRican Omnipurpose Detector for Innovative Techniques and Experiments) detector system by comparing both simulated and experimental results.

## 2. AFRODITE Detectors

The AFRODITE detection system is a medium sized array that has the ability to detect both low and high energy photons with a reasonable efficiency by using escape suppressed n-type high purity Germanium (HpGe) clover detectors and p-type LEPS (Low Energy Photon Spectrometer) detectors. Each clover detector consists of four n-type separate coaxial HpGe crystals that are packed in the configuration of a four leaf clover and placed in the same cryostat. In order to optimize close packing, the high purity Germanium crystals are tapered at the front face providing a 41 mm X 41 mm square face. A Compton suppression shield (BGO- Bismuth Germanate) surrounds the cover and rejects the Compton-scattered gammas. The AFRODITE frame has the shape of a small rhombicuboctahedron with sixteen detector positions. The target chamber also consists of the same geometry with thin Krypton windows. The clover detectors and escape suppressors were supplied by Eurisys and Crismatec respectively. The diameter and length of the HpGe before shaping are 51 mm and 71 mm respectively. The solid angle of the detector (percentage of $4\pi$) is 1.34% and the taper angle is 7% [7].

## 3. Geant4 model of AFRODITE detector system

Geant4 is an object oriented Monte-Carlo toolkit which is implemented in the C++ programming language [8]. It is used to simulate the interaction of particles with matter and it plays a major role in particle physics, nuclear physics, astrophysics and medical physics due to the versatility of the Geant4 code. The AFRODITE clover detector system was modelled using the Geant4 Monte-Carlo code (version 10.01.p03). The geometry of the germanium crystals, the BGO crystals, the rhombicuboctahedron shape target chamber, and the collimator were developed using CAD drawings. The complex geometry of the AFRODITE clover detector system was imported using the direct CAD model import interface, CADMesh [9, 10].

The Geant4 model of one crystal assembly with 16 BGO crystals shielding is shown in figure 1. In the Geant4 AFRODITE model, each BGO crystal is connected to a photo multiplier tube (PMT) but the PMTs were not included in the simulation studies. The Geant4 model of one of the clover detectors is shown in figure 2. For both the measurements and the simulations, eight clover detectors were used in the AFRODITE array. Four clovers were placed at $90^0$ and the other four clovers were placed at $135^0$ to the beam line.

## 4. Experiment

The measurements were carried out with the nuclear research division at iThemba LABS using the AFRODITE clover detector system. A proton beam of 95 MeV was used to hit a natural carbon target of thickness $8.40 \pm 0.07$ mg/cm$^2$. A thin target was selected to avoid multiple interactions. The target was prepared at iThemba LABS. An energy calibration was performed before the proton beam irradiation by using three standard gamma emitting sources, $^{152}$Eu,

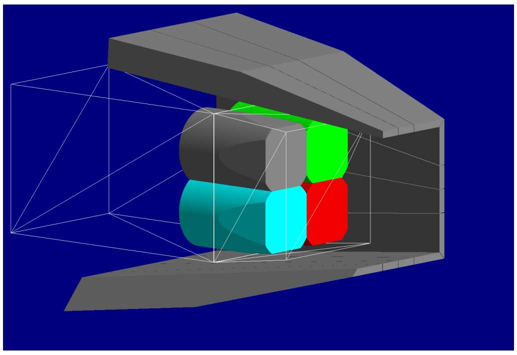

**Figure 1.** Geant4 model of the closely packed germanium crystals housed inside the Compton escape shielding

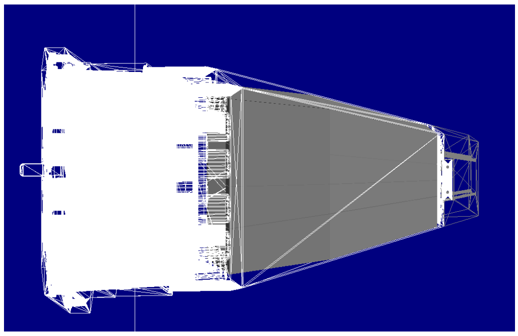

**Figure 2.** Geant4 model of one of the clover detectors

$^{60}$Co, and $^{137}$Cs. In order to reproduce the distance between the target and the detectors, the gamma sources were placed at the target position. Aluminium (0.88 mm thickness) and Copper (1.21 mm) absorbers were used to reduce the counts from low energy X-rays, with the copper placed closest to the source followed by the aluminium. The data were collected for 30 minutes for each gamma emitting source in direct detection mode. These collected data sets were used to calibrate the energy by considering 17 photo peaks from the above gamma sources. The same data set was also used to determine the absolute detector efficiency for each high purity germanium crystal [11].

## 5. Simulation

### *5.1.* Validation of AFRODITE model

In order to get accurate, reliable results from a Monte-Carlo model, validation of the model is a requirement. Therefore, the Geant4 model of the AFRODITE system was tested by using the standard gamma emitting source of $^{60}$Co as used in the experiment. The Geant4 model of the AFRODITE detector system attempted to model the experimental setup as closely as possible. The standard gamma source was generated using the Geant4 General Particle Source package (GPS) and placed at the target position. The GPS package is able to describe the primary source particle with various spatial, spectral, and angular distribution specification. The source was modelled as an isotropic gamma source and was run with 1.5 x $10^9$ histories.

### *5.2.* Prompt gamma simulation

For the simulations of prompt gamma production, the Geant4 model of the AFRODITE detector was used as in the experimental setup. When using the Geant4 Monte-Carlo code, it is important to select a suitable physics list. The QGSP_BIC Physics list package was used. The thickness for the carbon target was optimized as 0.5 mm in order to decrease the simulation time and to improve statistics. The prompt gamma simulation required 1.2 x $10^{12}$ proton histories and 1.8 x $10^5$ CPU hours.

## 6. Results and Discussion

### *6.1.* Measurement of prompt gamma emission

Figure 3 shows the raw data from the 95 MeV proton bombardment of the carbon target as measured by the 4 clovers placed 90 degrees to the beam direction. This spectra include all backgrounds (room background, background radiations from empty frame with beam on and beam off) measured during the experiment. All background radiation measurements were normalized according to the time acquisition and the integrated proton charge.

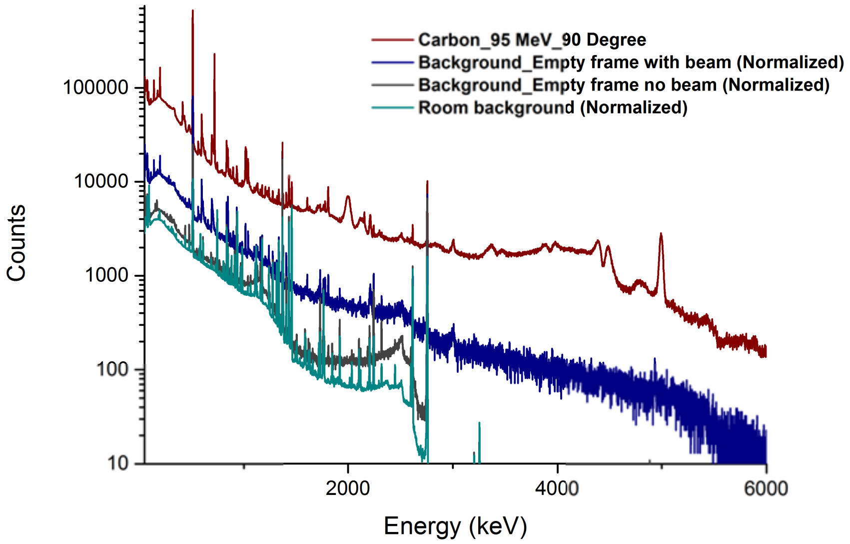


**Figure 3.** The red line shows the raw data for the 95 MeV proton bombardment of the carbon target, cyan color line is room background, the blue line indicates the background radiation from the frame with the beam on, and the gray line shows the background from the target frame with the beam off. These spectra were measured by the clovers placed at 90 degrees to the beam line. Normalization was done according to the time acquisition and the integrated proton charge.

### *6.2.* Validation of Geant4 AFRODITE model

The Geant4 Monte-Carlo model of the AFRODITE detector system was validated by using the standard gamma emitting source of $^{60}$Co as shown in figure 4. The simulated gamma spectrum was normalized against the experimentally obtained gamma spectra by comparing the number of gammas emitted by the gamma source (calculated from the source activity and the acquisition time) in the experiment and number of gamma histories used in the simulation. Both the experimental and simulated spectra have been Compton-suppressed.

Looking at the spectra in figure 4 the two major photo peaks as well as the Compton edge and back scattered peaks are aligned. Comparing the simulated and experimental spectra shows that the Geant4 AFRODITE model had a higher efficiency than the experiment since the simulated photo peaks were higher than the experimental photo peaks. Based on the total gamma production in the experimental and simulated spectra, the Compton shielding of the Geant4 model was determined to work about 15% better than actual Compton shielding detector.

### *6.3.* Prompt gamma spectrum comparison

The prompt gamma energy spectrum was simulated and experimentally measured at 95 MeV. In order to make an absolute comparison between the experimental and simulated results, three primary factors were considered: the difference in the number of incident protons, the difference in the target thickness and the absolute detector efficiency correction factor. Each of these elements resulted in a correction to the simulated spectra. First, the difference in the number of incident protons was corrected by multiplying the simulated spectra by the ratio of the total number of protons from the experimental run to the total number of simulated protons. Next,

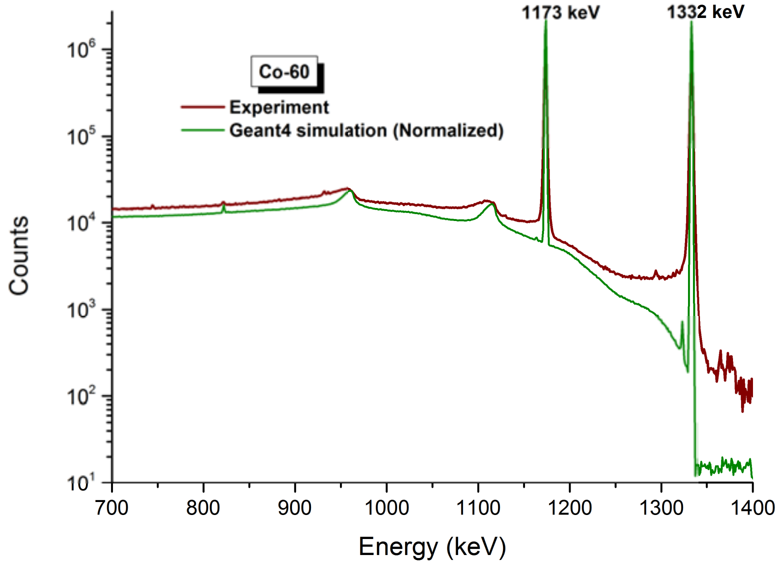


**Figure 4.** Comparison of the simulated and experimental gamma spectra from $^{60}$Co for the AFRODITE clover detector system. The green line shows the simulated spectrum and red line shows the experimental spectrum. Normalization was done according to the number of gammas emitted by the source in the experiment and number of gamma histories in the simulation.

the difference in the target thickness was corrected by multiplying the simulated spectra by the ratio of the experimental target thickness to the simulated target thickness. Lastly, the difference in the absolute detector efficiency needed to be corrected for each crystal individually based in the absolute detector efficiency correction factors. The simulated spectra from each crystal was divided by its respective correction factor. The combination of these corrections provided a way to make an absolute comparison of the experimental and simulated spectra, as shown in figure 5.

Overall, the two spectra align quite well, showing good peak agreement along the energy scale, particularly for the 4.438 MeV peak. The spectra also agree reasonably well in the number of counts with two noticeable gaps (between 2.0 and 3.5 MeV and above 4.5 MeV) where the simulation spectra is higher than the experimental spectra. The stretches where the simulations spectra are higher could be a result of the historic overestimation of the prompt gamma production in Geant4 or possibly the timing settings of the simulated Compton suppression. The total gamma production (determined by summing the gamma counts up to 6.0 MeV) for the experimental and simulated spectra in Figure 5 reveals that the simulated results were 40% higher than the total measured gamma production values. Finally, looking more closely at the 4.438 MeV $^{12}$C photo peak shows that the simulated peak is broader than the experimental peak.

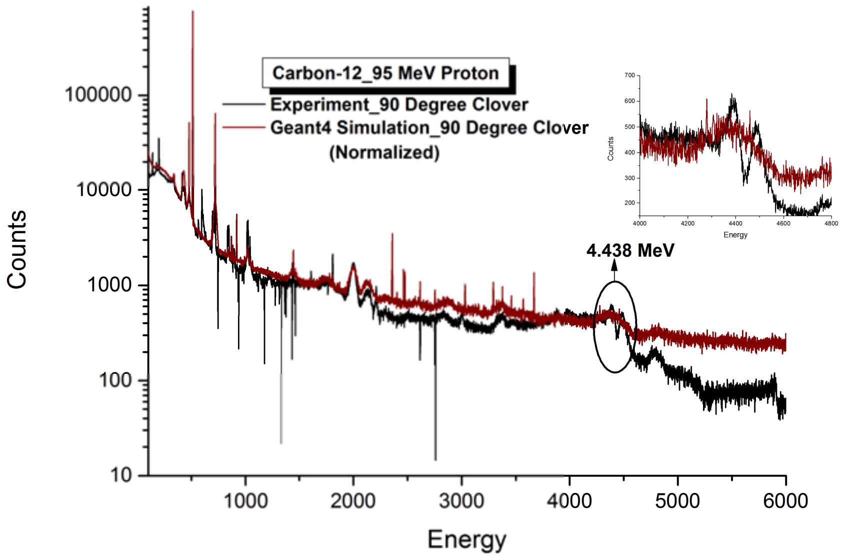


**Figure 5.** Gamma spectra comparison of the experimental and simulated results for a 95 MeV proton collision on the carbon target. The red line shows the corrected Geant4 simulated spectrum and the black line shows the experimental spectrum. Inset: Enlarged view of the 4.438 MeV gamma peak. Normalization was done according to the difference in the number of incident protons, the difference in the target thickness and the absolute detector efficiency correction factor.

## 7. Conclusion

The AFRODITE detector system was modelled using the Geant4 Monte-Carlo code (version 10.01.p03) and was validated by comparing to experimentally measured gamma spectrum using the standard gamma emitting source of $^{60}$Co. This validation of the AFRODITE model led to the conclusion our Geant4 AFRODITE model had a slightly higher efficiency than the actual detector setup. The overall absolute gamma energy spectra from the 95 MeV experimental and simulation runs were compared and displayed a 40% overestimation for the total gamma production values. Comparison of the 4.438 MeV peak showed an unsatisfactory discrepancy in the shape of the simulated peak for the prompt gamma production from carbon. The Geant4 AFRODITE model will be used to further investigate these highlighted issues with the hadronic physics lists for prompt gamma production.

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