Investigating the aberration found in 4.438 MeV $^{12}$C photo peak of the Geant4 simulated prompt gamma spectrum

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Abstract. The purpose of this study is to investigate the broad 4.438 MeV $^{12}$C photo-peak found in the Geant4 simulated prompt gamma spectrum from proton beam collision on a thin carbon target. The broad 4.438 MeV $^{12}$C peak has been reported in previous work using the AFRODITE clover detector performing an absolute comparison of measured and simulated prompt gamma production for a carbon target in the proton therapeutic range. The simulated prompt gamma spectrum was obtained for a 95 MeV proton beam collision on the carbon target by counting the emitted prompt gammas over a $4\pi$ solid angle using a Geant4(v10.01.p3) cross-section code with the suggested physics list for inelastic scattering in the proton therapeutic range (binary cascade model). This result was compared to prompt gamma spectra from other Geant4 inelastic scattering physics models. First, the default inelastic cross-section data set (Geisha) was compared to the Tripathi data set, producing basically identical spectra, indicating that the cross-section data set has no bearing on the binary cascade inelastic scatter model. Second, comparisons of the precompound model using an exciton number of 1 and the Geisha cross-section data set provides a 4.438 MeV photo peak that is closer to the experimental result. The precompound model with an exciton number of 1 and the default (Geisha) cross-section data set significantly narrowed the 4.438 MeV photo peak, giving the peak that most closely resembled measured data.

1. Introduction

Developments in radiation oncology and computer technology have made it possible for precision targeting of a tumour whilst increasing the tumour control probability. As a result, proton therapy has become increasingly popular due to the superior dose distribution of a proton beam. However, the advantage of proton therapy cannot be fully utilized without proper measurement of in-patient proton dose. Currently, there is no clinically applicable dose verification method available[1] [2] [3]. Detection of secondary gammas has been proposed as a potential method to measure in-patient proton dose since treatment protons stop within the patient as they deliver the dose [4]. There is on-going development of an imaging device to measure the scattered gamma-rays produced during a proton therapy treatment [5] [6]. During the design of this imaging device, Monte Carlo simulations have been performed to understand the production of these secondary (prompt) gamma-rays, particularly from tissue. Discrepancies have been
reported in the Geant4 prompt gamma production specifically in the most prominent elements (carbon-12 and oxygen-16) of tissue [3] [7] [8]. Previous work on prompt gamma production using a Geant4 model of the AFRODITE detector system [9] showed a broadened 4.438 MeV $^{12}$C photo-peak during the Geant4 AFRODITE simulation [10]. This study particularly will focus on investigating the broad 4.438 MeV $^{12}$C photo peak observed in the Geant4 simulated prompt gamma spectrum during proton collision on a thin carbon target.

2. Materials and Methods

2.1. Geant4 physics

There are 28 built-in physics lists currently available in Geant4. The user needs to select the appropriate physics processes according to the particle interaction and energy range of the incident particle. Custom built-in physics lists can be used by invoking individual physics models. There are also alternate Geant4 physics models available. In this simulation work, the physics lists were selected to measure the prompt gamma production in the proton therapeutic range (50 - 200 MeV); the chosen physics processes included inelastic scattering, elastic scattering, radioactive decay process, and electromagnetic interactions.

2.2. Comparison of Geant4 physics list

The recommended physics list for proton therapeutic range, particularly for inelastic scattering, is G4HadronPhysicsQGSP-BIC which was used in the Geant4 AFRODITE simulation study [10]. This work compared the prompt gamma spectra obtained using this suggested physics model against other available Geant4 models. The cross-section code, which is basically the AFRODITE code without the complex clover detector geometry, was used to compare the prompt gamma production. The physics and the incident proton beam of the cross-section code is identical to the Geant4 model of the AFRODITE code. Consequently, the cross-section code is able to count the emitted prompt gammas over a 4π solid angle, cutting down significantly on time required for each simulation. The cross-section code was run for a 95 MeV proton beam collision on the natural carbon target of thickness 0.5 mm using the default physics list (binary cascade-inelastic scatter model) and other custom built in physics models.

3. Results and Discussion

First, let’s start by comparing the inelastic cross-section data sets for 95 MeV proton collisions with a thin carbon target. The default inelastic physics model (G4HadronPhysicsQGSP-BIC), which uses the Binary Cascade (BC) model remained fixed, while the Geisha (default) and Tripathi inelastic cross-section data sets were compared, as shown in Figure 1. The result is that the two spectra are basically identical, indicating that the cross-section data set has no bearing on the Binary Cascade inelastic scatter model.

Second, the precompound model (PRECO) was compared against the binary cascade model (BC) using the default cross-section data set (Geisha), shown in figure 2. The number of prompt gamma counts was suppressed for the precompound model (both overall and in the 4.438 MeV peak) while the width of the 4.438 MeV peak was unchanged. Figure 2 also shows that the same broad (and suppressed) peak is observed when the Tripathi cross-section data set is used with the precompound model.

Finally, the exciton number was changed in the precompound model from the default value of 2 to 1 with the results shown in figure 3. The precompound model with exciton 1 is able to significantly narrow the 4.438 MeV photo peak for both inelastic cross-section data sets (Geisha and Tripathi). The spectra from the precompound model with the two different cross-section data sets are very similar with the only difference being a slightly higher number of prompt
Figure 1. Prompt gamma spectrum comparison for the binary cascade model with two different inelastic cross-section data set (Geisha and Tripathi) using the default exciton number of 2. Prompt gammas produced by a 95 MeV proton beam collision on a natural carbon target.

Figure 2. Binary cascade prompt gamma spectrum comparison against the precompound model using the Geisha and Tripathi cross-section data set. Prompt gammas produced by a 95 MeV proton beam collision on a natural carbon target.

gammas from the Tripathi data set. While this difference is slight, using the Geisha cross-section data set is recommended due to the tendency for Geant4 simulations to overestimate prompt gamma production values [11]. Based on these comparisons, the precompound model using an exciton number of 1 and the Geisha cross-section data set provides a 4.438 MeV
photo peak that is closer to the experimental result, both due to the narrower peak and the
suppressed prompt gamma production. This appears to be a better choice for proton collisions
in the proton therapeutic range with carbon than the recommended QGSP-BIC physics list for
Geant4 (version 10.01.p03).

![Graph](image)

**Figure 3.** Binary cascade prompt gamma spectrum comparison against the precompound
model with modified number of exciton as 1 using the Geisha and Tripathi cross-section data
set. Prompt gammas produced by a 95 MeV proton beam collision on a natural carbon target.

While the precompound model (with exciton number of 1) provides a narrower peak, the
reason for the broad peak using the default physics lists is still not clear. Figure 4 provides
a glimpse into the reason behind the broad peak by disabling the Doppler Broadening of the
prompt gammas, producing sharp gamma peaks. The 4.438 MeV gamma peak is very noticeable,
particular for the exciton = 1 spectra, but there is a second peak at 4.33 MeV that is equally
prominent in the exciton = 2 spectra. This peak comes from the following simulated reactions
\([^{12}\text{C}(p, d)^{11}\text{C}^*] \text{ or } ^{12}\text{C}(p, np)^{11}\text{C}^*\), which have been artificially amplified through the Geant4
Physics processes. Unfortunately, no option exists to disable Doppler Broadening for the Binary
Cascade model, but simulations have shown that the \(^{11}\text{C}\) reactions listed above also occur at an
equal rate to the expected \(^{12}\text{C}(p, x)^{12}\text{C}^*\) reaction, thus explaining the broad 4.438 MeV gamma
peak.
Figure 4. Prompt gamma spectrum with Doppler broadening ignored for the precompound model using the Geisha inelastic cross-section data set with the carbon target and 95 MeV incident proton. Note the sharp increase in the 4.438 MeV peak when the exciton number is changed to 1.

4. Conclusion
Using the simplified cross-section code, which measured the prompt gamma production over a $4\pi$ solid angle, different physics models and inelastic cross-section data sets were compared to investigate the broad 4.438 MeV $^{12}$C photo-peak. Prompt gamma spectra were simulated for the carbon target using the Geant4 binary cascade and the precompound models, while selecting two different inelastic cross-section data sets (Geisha-default and Tripathi) as well as modifying the exciton number in the precompound model between 1 and 2 (default). The precompound model with an exciton number of 1 and the default (Geisha) cross-section data set significantly narrowed the 4.438 MeV photo peak. Using the non-standard exciton number of 1 suppressed the unnatural 4.33 MeV peak that broadened the 4.438 MeV peak produces a photo-peak that more closely resembles the measured results [9].
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