Modeling Microhotspot Formation from $^{12}C(\gamma, \alpha)^{8}Be \rightarrow 2\alpha$ Reactions: A Theoretical and Experimental Approach

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Introduction

Radiotherapy using high-energy photons, particularly at 15 MeV, plays a crucial role in cancer treatment, and understanding the underlying nuclear reactions is essential for optimizing its effectiveness. One significant reaction is the $^{12}C(\gamma, 3\alpha)$ process, which has a threshold energy of 7.4 MeV. Such reactions have important clinical implications, as the interaction of α particles with biological tissue—particularly DNA—serves as a primary target for high linear energy transfer (LET) radiation. When ^{12}C is excited above the α separation energy, the resulting breakup releases kinetic energy in the form of α particles, raising concerns about the effects of photon-induced breakup of ^{12}C in tissue during radiotherapy.

However, these effects are challenging to measure directly in clinical conditions due to their small scale. Additionally, no reliable anticipations can be made regarding their impact, as the spectrum and cross sections of these reactions remain unknown. While the absorbed dose from photon-induced nuclear reactions must be measured to evaluate the impact of high LET radiation on tissue, previous measurements by Resmi et al. (2024) have highlighted the significance of this process. In the present study, these findings have been theoretically reproduced using fresco CDCC CRC calculations, which have been employed to simulate and study the behavior of microhotspots. This research offers critical insights into the nuclear processes involved in high-energy photon therapy and their potential biological effects.

FRESCO Calculations

The theoretical calculations for the $^{12}C + \gamma$ entrance channel couple the initial state to the final $\alpha + ^{8}$ Be states through the E_1 electromagnetic mode. This framework is implemented using FRESCO CDCC-CRC calculations, where the entrance channel is defined with a pseudopotential for photons and $\alpha + ^{8}$ Be as the exit channel. A Gaussian potential with parameters $V_0 = 106$ MeV and $R_0 = 2.236$ fm describes the $\alpha + \alpha$ breakup continuum. The ground state (0^+) and excited state (2^+ at 3.03 MeV) of ^{8}Be are characterized using a Woods-Saxon potential.

The breakup continuum generated by the $\alpha + \alpha$ clusters is analyzed through discretization based on wave number and angular momentum, where the wave number k is defined as $k = \frac{\sqrt{2\mu E_x}}{\hbar}$. The states are generated up to $k^{-1} = 0.7$ fm with a bin width of 0.175 fm. All states in the exit channel are coupled to the entrance channel via the E_1 mode, with spectroscopy factors of unity for CRC states and an average of 0.75 for CDCC states. The FRESCO calculations yield cross sections at 60°, which are converted to γ beam incident energy and compared with Measurement by Resmi et al [1].

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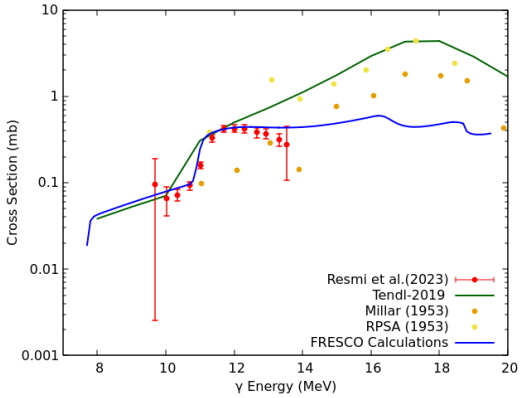

FIG. 1: FRESCO calculated cross sections along with previous measurements

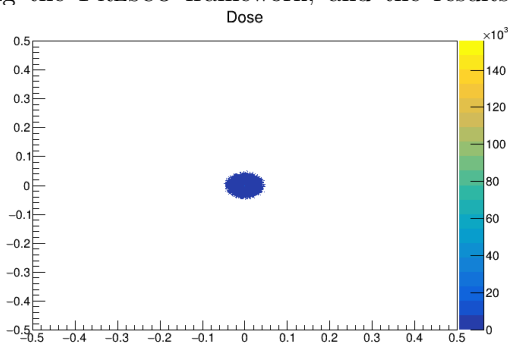

FIG. 2: Simulated $\mu-$hotspot profile corresponding to a single event

Profiling $\mu-$hotspot in Geant4

The behavior of microhotspots formed during the interaction of high-energy photons with tissue has been simulated using Geant4. This simulation incorporates theoretically calculated differential and double differential cross sections, which have been optimized to reproduce experimental cross sections, providing a robust numerical input for the model. In this context, real tissue is modeled within Geant4, simulating a typical treatment flux of 10^{11} photons/cm^2.

The simulation focuses on scoring the energy deposit corresponding to the volume of tissue affected and the hit vertices of the interacting photons. By analyzing these energy deposits, the study aims to understand the spatial distribution and characteristics of the microhotspots formed during the radiation treatment, offering insights into their potential biological impact and contributing to the optimization of radiotherapy techniques. This approach allows for a comprehensive assessment of the interactions occurring at the microscopic level, which is crucial for improving the efficacy and safety of radiation therapies.

Results and Discussion

The cross sections for the reaction $^{12}\mathrm{C}(\gamma,\alpha)^{8}\mathrm{Be} \rightarrow 2\alpha$ were calculated using the FRESCO framework, and the results are depicted in FIG. 1 alongside previous experimental measurements. The comparison reveals a strong alignment between the theoretical calculations and the experimental data up to an energy of 20 MeV. This correspondence indicates that the theoretical model effectively captures the essential dynamics of the reaction, reinforcing the reliability of the methodologies employed, including optimized parameters derived from the theoretical analysis.

Additionally, FIG. 2 illustrates the dose profile of the microhotspot, simulated using Geant4 based on the present theoretical framework. The profile exhibits a Poisson-like distribution, reflecting the continuum energy spectra of the emitted α particles. Notably, the standard deviation of the distribution is approximately 3 micrometers, which corresponds to the typical size of a cell. The peak dose in this simulation reaches 10^3 Grays, representing a potentially lethal dose. This information highlights the critical impact of microhotspots in radiotherapy and their implications for biological tissue.

References

[1] Resmi et al. Proc. DAE Symp. Nuc. Phys. Vol. 67. B8. p377 (2023)