Impact of Nuclear Reactions on Proton Therapy Dose Distribution

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INTRODUCTION

Proton therapy for cancer treatment gained significant attention due to its high conformity towards dose deposition. Proton therapy is performed by utilizing high-energy proton beams up to 250 MeV. The dose conformity in proton therapy is achieved by the benefit of the Bragg peak. The dosimetric calculations for the treatment are performed by the stopping powers based on the Bethe-Bloch formalism. However, the Bethe-Bloch formalism is limited to electronic energy losing mechanisms and energy loss in the nuclear electric field. However, in practice, the high energy proton beam initiates many nuclear reactions while interacting with the nuclei present in the tissue. The ejectiles in the reaction and reaction residue carry a significant amount of kinetic energy, with a momentum path different from that of the primary beam and produce a significant amount of dose, besides the primary dose produced by the Coluomb interaction. The ejectiles and residues carry a different LET than the primary proton beam, which spoils the conformity and other criteria in the radiotherapy. Hence the dose is unjustified[1].

To the best of our knowledge, no measurements are existing for the dose contribution by the nuclear reaction component in tissue during proton therapy, due to the experimental challenges. Currently, the dosimetric calibrations for protons are performed on water, which is considered tissue equivalent at the atomic level. While, in nuclear level, water and tissue are entirely different, as the tissue has more elements and its isotopes.

Further, based on the Monte Carlo simulations, some analyses existing on the nuclear reaction components of proton therapy[2]. However, due to the adoption of empirical models for calculating the cross sections and angular distributions, they are not much successful in addressing the exact energy and angular distributions of the reaction products. Further, these studies hold only the compound nuclear reaction component, which is inappropriate to explain the exact energy and angular distributions of the produced secondary particles at higher energies. Further, the experimental energy and angular distributions are not available to optimize the theoretical (empirical and statistical) models for high energies and this limits the simulations in predicting the dose distributions accurately.

This limitation has been attempted in the present study by utilizing the optical models followed by statistical calculations for estimating the cross sections and the ejectile spectrum. The current study incorporated the direct and pre-equilibrium components of nuclear reactions, along with the compound nuclear component. The statistical calculations are optimized based on the available experimental residue cross sections. The details are in the following sections.

MATERIALS AND METHODS

The out of field dose distribution by the secondary reaction products were calculated by simulating the condition in Geant4. The ejectile spectrum corresponding to each element on p-^{nat}C, p-^{nat}O, p-^{nat}N, p-^{nat}Ca and p-^{19}F are estimated using Talys statistical model calculations. The available residue cross sections for proton induced reactions were used to optimize the Talys-1.96 model parameters corresponding each projectile target combination. The residual cross sections available in the energy range of 0-120 MeV has been used[3].

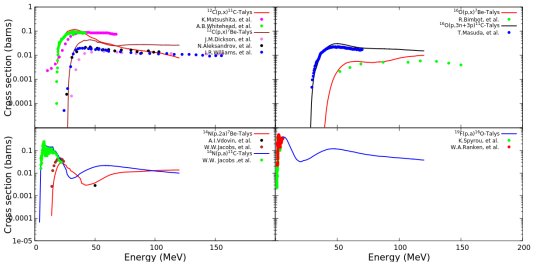

Figure 1: *: Experimental and Talys calculated residue cross section of interaction of proton of energy range 1-120 MeV with a)^{12}C, b)^{16}O, c)^{14}N and d)^{19}F.*

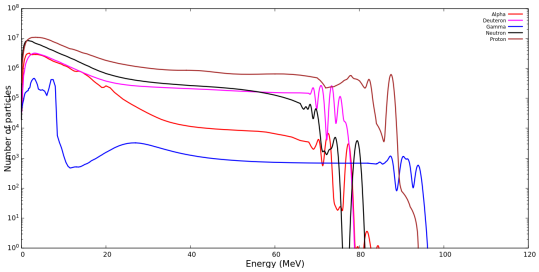

Figure 2: *: Calculated particle spectra of α, γ, d, p and n from ICRU-A150 tissue, induced by 100 MeV protons.*

The ejectile particle spectrum in lab frame corresponding to proton induced reactions on ICRU-A150 tissue is calculated for proton energy of 100 MeV based on the optimized model parameters in $d\sigma/dE$ units. This is then converted into yield per particle energy bin accounting the elemental weight fraction in ICRU-A150 tissue, Number density and beam current. These particle yield spectra corresponds to proton, neutron, deuteron, alpha and gamma are loaded into Geant4 and the angular distribution is defined. The practical beam profile, in the form of a Gaussian, with FWHM of 3 mm is also accounted. The spatial dose distribution in the 100 MeV plane has been calculated and analysed.

Optical potential by Koning and Delaroche has been used for the calculations. The potential parameters were taken from RIPL-3 compilation.The microscopic level densities based on HFB model calculations using Gogny force were used for the compound nuclear part. The pre-equilibrium is accounted by the exciton model with optical model based collission probabilities. The direct reaction component has been optimized to reproduce the experimental data by adjusting the scaling parameters for knockout reactions.

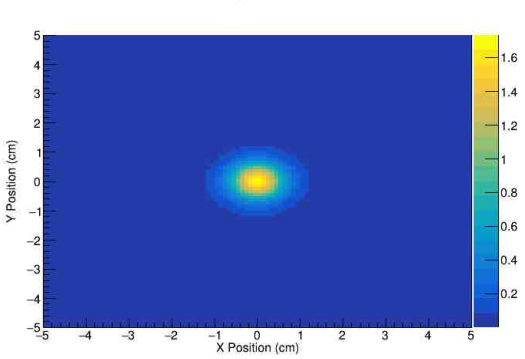

Figure 3: *: Simulated spatial distribution of dose due to the proton induced nuclear reactions on ICRU-A150 tissue at 100 MeV plane.*

Results and Discussion

Talys-1.96 nuclear reaction model code has been optimized for addressing p-^{nat}C, p-^{nat}O, p-^{nat}N, p-^{nat}Ca and p-^{19}F excitation function with accounting compound nuclear, pre-equilibrium and direct reactions. The optimized cross sections along with experimental data is presented in Figure.1 . The theoretical spectrum of secondary particles at 100 MeV proton energy, corresponding the ICRU-A150 tissue is given in Figure.2. The final dose distribution by the secondary particles produced in proton induced nuclear reactions on ICRU A150 tissue is shown in Figure.3. This shows a significant contribution of out of field dose due to the fragments produced through nuclear reactions. Our study is confined to nuclear reactions and Rutherford scattering is not accounted. However it is also contributing much to out of field dose since it's cross section is high compared to the nuclear reaction cross sections. The current study is limited to theoretical only, an accurate measurement on double differential cross sections is required for an accurate determination of the out of field contribution.

References

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