Optimization of GEANT4/GATE hadronic models for in-beam PET dose monitoring in carbon ion therapy

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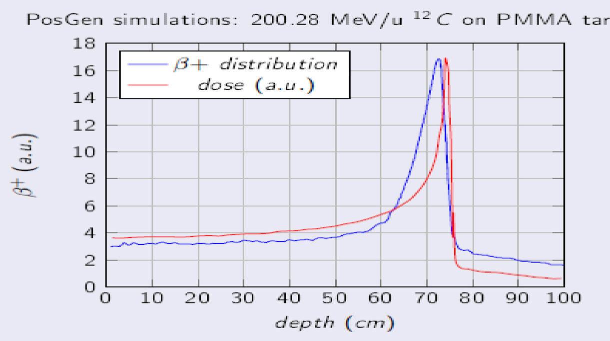
The GATE simulation toolkit (GATE v6) based on GEANT4 v9.4 has all the necessary features to model in-beam Positron Emission Tomography (PET). In this work, we characterize the accuracy of the physics models included in GEANT4 v9.4 to describe β^+ emissions induced by ^{12}C ion beam that give rise to the detected signal in in-beam PET monitoring of carbon ion therapy.

Carbon ion therapy

Carbon ion therapy is a new type of radiotherapy treatment for cancer using Carbon ion beams. It is especially appealing for radioresistant tumors or tumors close to organs at risk.

Principle of in-beam PET monitoring

- Primary ions interact through nuclear collisions with the target
- Among the secondary particles resulting from these interactions, β^+ emitters are produced (^{10}C ($T_{1/2} \sim 20$ s), ^{11}C ($T_{1/2} \sim 20$ min) and ^{15}O ($T_{1/2} \sim 2$ min) mostly)
- The β^+ activity spatial distribution is closely correlated to the dose distribution



- Treatment monitoring: beam induced β^+ activity map is measured using PET

P.CRESPO PhD Thesis 2005

GEANT4 and GATE toolkits

- GEometry ANd Tracking (GEANT4) is a toolkit dedicated to the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, and studies in medical and space science.
- GEANT4 Application for Emission Tomography (GATE) is an advanced open-source software developed by the international OpenGATE collaboration and dedicated to numerical simulations in medical imaging and radiotherapy.
  - ⇒ It encapsulates the Geant4 libraries in a modular versatile, scripted simulation software

Agostinelli *et al.* GEANT4, a simulation toolkit. NIM A 506 (2003) 250-303

Allison *et al.* Geant4 developments and applications. IEEE Trans. Nucl. Sci 53 (2006) 270-278

Jan *et al.* GATE V6: a major enhancement of the GATE simulation platform enabling modelling of CT and radiotherapy. Phys. Med. Biol. 56 (2011) 881-901

Jan *et al.* GATE: a simulation toolkit for PET and SPECT. Phys. Med. Biol. 49 (2004) 4543-4561

http://www.opengatecollaboration.org

Hadronic models

Two models suitable for nuclear collision description are available in GEANT4 v9.4: Binary Cascade (BiC) and Quantum Molecular Dynamics (QMD) models.

Methods

Experimental and simulated production rates were compared considering a ^{12}C beam in a 30×10×10× cm^3 PMMA target, with beam energy of 212.12 MeV/u, 259.5 MeV/u and 343.46 MeV/u. The relative deviation between experimental yield $\mathcal{Y}$ and simulated yield $\mathcal{Y}_{model}$ was calculated as $\epsilon_{model} = \frac{|\mathcal{Y} - \mathcal{Y}_{model}|}{\mathcal{Y}}$.

- green values correspond to relative deviation < 20 %
- orange values correspond to relative deviation between 20 % and 40 %
- red values correspond to relative deviation > 40 %

Experimental and simulated production rates as a function of depth were compared considering a ^{12}C beam in a 30×10×10× cm^3 PMMA target, with beam energy of 215 MeV/u, 260 MeV/u and 337 MeV/u. Only shapes of the profiles were considered.

β^+ production rate

The table below shows the integrated production rates over the whole PMMA target

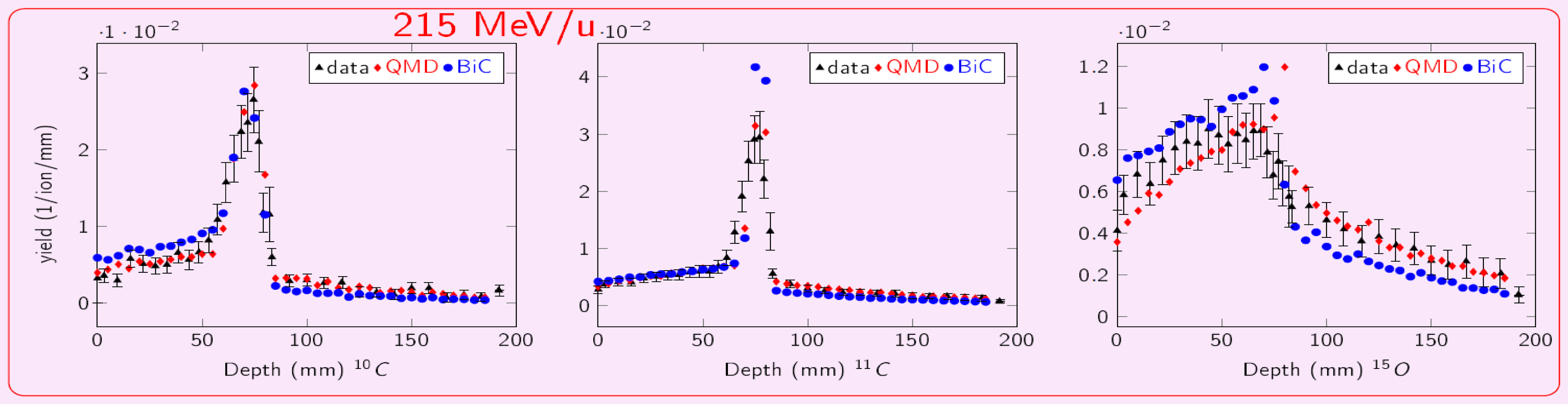
212.12 MeV/u	$\mathcal{Y}$ [10^{-2}/ion][1]	ϵ_{QMD} [%]	ϵ_{BiC} [%]
^{10}C	(0.8±0.03)	25	200
^{11}C	(10.5±1.3)	15	18
^{15}O	(2.1 ± 0.3)	5	22
259.5 MeV/u	$\mathcal{Y}$ [10^{-2}/ion][1]	ϵ_{QMD} [%]	ϵ_{BiC} [%]
^{10}C	(1.2±0.3)	16	46
^{11}C	(14.7±1.6)	12	20
^{15}O	(3.1±0.4)	6	35
343.46 MeV/u	$\mathcal{Y}$ [10^{-2}/ion][1]	ϵ_{QMD} [%]	ϵ_{BiC} [%]
^{10}C	(1.5±0.3)	53	46
^{11}C	(19.9±2.4)	5	12
^{15}O	(5±0.4)	18	16

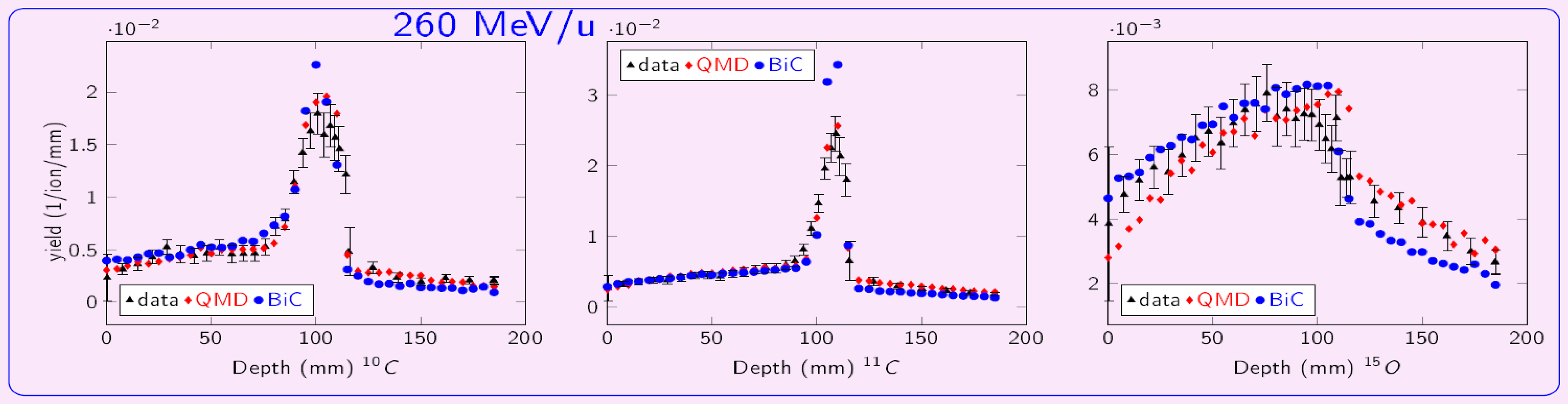
⇒ For most experimental data, QMD model yields more accurate results than BIC model

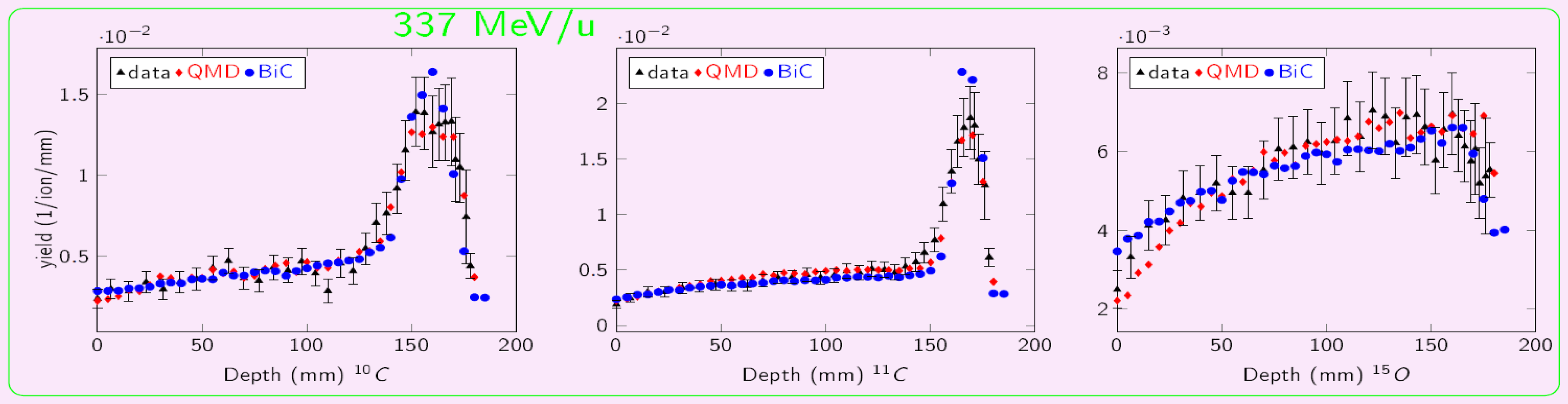
[1] K.Parodi *et al.* PhD Thesis 2004.

β^+ emitter yields as a function of depth in a PMMA target

The plots below show the production rate as a function of depth in a PMMA target







⇒ For most profiles QMD model better reproduces the experimental data than the BiC model

Data shared in the framework of WP6 ENVISION European project.

Conclusions

- The QMD nuclear collision model included in GEANT4 v9.4 accurately reproduces the β^+ production rates experimentally measured as a function of depth for different ^{12}C beam energies
- GATE/GEANT4 appears as a promising tool to accurately model in-beam PET monitoring of carbon ion treatment and to study the potential of this innovative treatment monitoring approach