Recent developments of FLUKA for hadron therapy

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Outline

• Introduction to FLUKA

• Nuclear reaction cross sections in FLUKA for helium ions

• Radiobiological studies in FLUKA for hadron therapy
FLUKA

• a fully integrated particle physics Monte Carlo code

• simulations of particle transport and interactions with matter

• widely used in physics for:
  - particle accelerator and detector design
  - shielding
  - dosimetry
  - calorimetry
  - activation
  - medical applications

LHC at CERN

https://home.cern/topics/large-hadron-collider
Medical applications

At CNAO (Italy), HIT and MIT (Germany), cancer patients are treated with protons and carbon ions.

In those facilities FLUKA is used:
- to **generate input data** for the treatment planning systems,
- to **validate the dose calculations**.

Mairani A et al PMB 58 (2013) 2471-2490
Medical applications

Single Bragg Peaks

Data acquired at HIT:

Ep = 54.10 MeV
142.66 MeV
221.05 MeV

EC = 200.28 MeV/u
299.94 MeV/u
430.10 MeV/u

Medical applications

*Spread out Bragg Peaks*

Tessonnier T *et al*

PMB.62(2017) 6579-6594
Overview

- Introduction to FLUKA
- Nuclear reaction cross sections in FLUKA for helium ions
- Radiobiological studies in FLUKA for hadron therapy
Helium ion therapy

The interest on helium ions is growing fast in the last years.

The Heidelberg Ion-Beam Therapy center (HIT, Germany) is planning to use helium ion beams for radiotherapy in the near future.

Helium ions vs protons:
- Less scattering
- Wider penumbra
- Higher costs

Helium ions vs carbon ions:
- Lower RBE
- Less fragmentation tail
- Lower costs
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AIM:
Improvements of the nuclear reaction model in FLUKA for helium ions
Experimental setup

**Incident beam**: He ions

Exp. setup mounted @ HIT
Experimental setup

**Incident beam**: He ions

**Target**: thin graphite, silicon, silicon dioxide

Exp. setup mounted @ HIT
Experimental setup

**Incident beam**: He ions

**Target**: thin graphite, silicon, silicon dioxide

**Detector**: ΔE/E telescope (provided by GSI)
Experimental setup

**Incident beam**: He ions  
**Target**: thin graphite, silicon, silicon dioxide  
**Detector**: ΔE/E telescope (provided by GSI)

Experimental measurements:  
- mass changing cross sections \((\sigma_{\Delta A})\)  
- charge changing cross sections \((\sigma_{\Delta Z})\)

\[ ^4\text{He} + T \rightarrow X + R \]

**Note**:  
Primary helium ions that interact in the target without undergoing fragmentation are not measured in the experiments  
\[ ^4\text{He} + T \rightarrow ^4\text{He} + T^* \]
Results

Discontinuity between BME and rQMD

Note:
Primary helium ions that interact in the target without undergoing fragmentation are not measured in the experiments

\[ {}^4\text{He} + T \rightarrow {}^4\text{He} + T^* \]
Results

(a) $^4\text{He} + ^{12}\text{C}$

(b) $^4\text{He} + ^{16}\text{O}$

therapeutic energy range

Article in preparation
Results

(a) 100 MeV/u $^4$He in water

(b) 190 MeV/u $^4$He in water

Article in preparation
Results

(c) 100 MeV/u $^4$He in water

Relative differences from $\sim 3\%$ to $\leq 0.5\%$

(d) 190 MeV/u $^4$He in water

Relative differences from $\sim 8\%$ to $\leq 1.6\%$

Article in preparation
Results

Article in preparation

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OMA International Conference on Medical Accelerators
04-06 September 2019
Giulia Aricò
Results

Article in preparation
In some cases, **helium ion therapy** can be a viable alternative to proton and carbon ion therapy.

- Prior to the use of helium ions for clinical applications, their physical and biological properties have to be well known.

- **New experimental data** in the therapeutic energy range were used to **benchmark** the FLUKA nuclear reaction cross sections.

- An additional **renormalization** factor was considered to calculate the total reaction cross section from the fragmentation cross section (measured in the experiments).

- Improvements in the FLUKA nuclear reaction cross sections were needed for more accurate dose calculations.
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Definition of RBE

Relative biological effectiveness:

\[ RBE = \frac{D_Y}{D_{ion\text{ iso-effective}}} \]

RBE depends on:
- LET
- Dose
- Particle type
- Radiosensitivity
Radiobiological models

**Protons:** RBE = 1.1

**Carbon and Helium ions:** radiobiological models

- Local Effect Model (LEM) used in clinics in Europe (developed at GSI)
- Microdosimetric Kinetic Model (MKM) used in clinics in Japan
- Biophysical ANalysis of Cell death and chromosome Aberrations (BIANCA) developed at the University and INFN of Pavia
Radiobiological models

- **Local Effect Model I (LEM I):**
  
  the damage in a cellular sub-volume is related to the expected energy deposition in that sub-volume,
  
  tested against survival curves of CHO and V79 cells in vitro, and against in vivo data of rat spinal cord.

- **Biophysical ANalysis of Cell death and chromosome Aberrations (BIANCA):**
  
  the cell death is directly correlated to the chromosome aberration,
  
  tested against survival curves of V79, AG01522, U87 and CHO cells in vitro.
Benchmarking of BIANCA

Survival of V79 cells irradiated by carbon ion beams of different (dose-averaged) LET [keV \(\mu\text{m}^{-1}\)]

Benchmarking of BIANCA

RBE at 10% and 50% survival of V79 cells

Method

1) FLUKA simulations + radiobiological model (tabulation of $\alpha$ and $\beta$ for mixed ion fields)

2) Scoring of $\alpha$, $\beta$, and absolute dose in FLUKA, in each bin, in water or in a patient case

3) Computation of survival cells:

$$-\ln(S) = \begin{cases} \frac{\bar{\alpha}D + \bar{\beta}D^2}{\bar{\alpha}D_t + \bar{\beta}D_t^2 + (D - D_t)s_{\text{max}}} & D \leq D_t \\ \frac{D - D_t}{s_{\text{max}}} & D > D_t \end{cases}$$

$$D_{\text{RBE}} = \begin{cases} \sqrt{-\ln(S)/\beta_X + (\alpha_X/(2\beta_X))^2 - (\alpha_X/(2\beta_X))} - \ln(S) \leq -\ln(S_t) \\ (-\ln(S) + \ln(S_t))/s_{\text{max}} + D_t & -\ln(S) > -\ln(S_t) \end{cases}$$

and RBE: 

$$\text{RBE} = \frac{D_{\text{RBE}}}{D}$$

Similar approach* for LEM and BIANCA, but:

different $\alpha$, $\beta$, $\alpha_X$ and $\beta_X$ values, and no $D_t$ and $S_t$ in BIANCA

Comparison with SOBP experimental data

Acrylic container 5 cm x 10 cm x 16 cm. Cells grown as monolayers on 25 cm² polyethylene slices.
Chinese hamster ovary cells (CHO-K1) grown under standard conditions.

Measurements performed at HIT (proton and carbon ions) or at GSI (helium ions).

Experimental data were compared with TRIP+LEM predictions.

Experiment from Elsässer et al 2010, Int J Radiat Oncol Biol Phys 78(4) 1177-80
Results

Surviving fraction for CHO cells in a typical two-port irradiation with **protons** (left) and **carbon ions** (right)

![Graph showing surviving fraction for CHO cells](image)

Please see **Wioletta Kozlowska**’s poster, **P57**, for examples in **patient** cases

Helium?
Results

Survival of V79 cells irradiated by helium ion beams of different (dose-averaged) LET [keV µm\(^{-1}\)]

Surviving fraction for CHO cells in a one beam irradiation with helium ions

Summary and Conclusions

BIANCA is a biophysical model developed in Pavia that can predict chromosome aberrations and cell death.

- BIANCA can be used for cell survival and RBE predictions, in principle for any cell line.
- Following interface with FLUKA, BIANCA was used to predict cell survival in SOBP, with proton, carbon and helium ions.

- We plan to complete this work for helium ion beams,
- and to benchmark BIANCA against *in vivo* chordoma data.
Thanks for your attention

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