Hadron-therapy: use of Monte Carlo FLUKA method to investigate the dose deposition profile of carbon and helium ions in a water phantom

BAKOLIA TOMFEY ESSAKPA*[1], RAJAA SEBIHI[1], ABDESSAMAD DIDI[2], ADAMBOUNOU KOKOU[3], TCHAOU MAZAMAESSO[4]

[1] ESMaR, Department of Physics, Faculty of Sciences, University Mohamed V, Rabat, Morocco.

[2] National Centre for Nuclear energy, science and. Technology, Morocco.

[3] University of Lome, Togo.

[4] University of Kara, Togo.

*E-mail: bakodeo@gmail.com

Abstract

In this study on radiotherapy by charged particles, it was a question of using the Monte Carlo FLUKA method to study and compare the deep dose deposit of carbon and helium ions in order to evaluate the potential benefits that these particles can contribute to radiotherapy. The dosimetry aspect studied in this study was the deep dose deposition. The results of this study showed the shapeof the dose deposition curve in depth of the two particles was practically identical but certain differences such as the difference in dose deposition in depth at identical energy and the presence of a fragmentation of the ions. Carbon was observable.

Keywords: Monte Carlos code, FLUKA, dose, hadron therapy, hadrons, depth, carbon, helium

Introduction

The use of ions has become a common practice in the field of oncology due to its multiple advantages. This new complementary technique to radiotherapy is known as hadron therapy.
Its development began with the introduction of protons in medical areas 1946 with the work of Wilson [1]. It uses charged particles such as protons, and other ions heavier than protons, improperly called heavy ions, such as helium, carbon, oxygen or neon to irradiate tumor cells. This modality attracts attention for two reasons. The first one is ballistic which ensures a good targeting of the tumor and a good protection of the surrounding healthy tissues. The second one is biological which leads to a more important cellular damage than the x- and ɣ-photon radiotherapy. The advantages of this technique have been demonstrated through the study of dosimetry characteristics(TEL, EBR, oxygen effect) and the evaluation of the dose deposited by these radiations in different media For these purposes the scientific world has several methods of dosimetry evaluation. Among these methods we can mention the numerical evaluation techniques based on Monte Carlo codes which were proposed for the first time in the 1777 by Comte Buffon [2]. Monte Carlo methods use random numbers to solve any problem having a probabilistic interpretation. This random technique of individual tracking of

particles has known its real development at the beginning of the 19th century during the First World War. On this project we decided to compare the dose deposition of carbon ions which are currently used in hadron therapy centers with protons and helium which is almost abandoned using the numerical evaluation technique more precisely the Monte Carlo code FLUKA. The details of the Monte Carlo code FLUKA will be discussed in the Materials and Methods section.

Materials and Methods

The advent of hadrons in the treatment of cancers follows the failures recorded in conventional radiotherapy for reasons of tumor radio resistance, the delicate localization and difficult access to certain tumors or for reasons of tissue growth in young people (pediatric tumors). The use of X-rays and gamma rays causes enough undesirable irradiation by depositing energy from the surface to the depth where the tumor is located. Protons, carbon ions, and helium [3] are the hadrons that are most commonly used in particle radiation therapy to compensate for the excess radiation generated by photons. Although all these particles have points in common (the localized deposition of the dose at the end of the path and a very low lateral dose loss), however, it is not excluded to observe small variations which may be linked to the nature of the intensity of incident beam. The objective of thisstudy is to use the FLUKA Monte Carlo method to evaluate and compare the dose deposition ofcarbon and helium ions in a water phantom in order to prove the effectiveness of the use of these particles. The numerical method of dose determination is becoming an increasingly recurrent practice in radiotherapy and particularly in hadron therapy. The implication of this technique is explained by its accuracy in dose estimation, the reduction of calculation uncertainties, the individual follow-up of each particle entering the patient and especially a perfect representation of the real physical phenomena governing the interaction of charged particles and matter. The Monte Carlo code FLUKA [4] is one of the most solicited numerical techniques in medical practice, along with the Geant4, PENELOPE MCNP, PHITS codes [5-7].

In this study two types of mono-energetic particles (carbon and helium) of varying intensity (100, 200 300, and 400 MeV) will be used to irradiate an identical target of the same configuration and composition modeled by a simple geometry formed by a rectangular parallelepiped RPP (20 x 20 x 40)cm3 parallel to the axis of propagation Z containing water and surmounted by two spheres of respective radius 10000cm made of vacuum and 100000cm containing air called the "black hole" as shown in Figure1. The purpose of the black hole is to neutralize any particles entering the activearea by absorption. The beams of normal distribution (FWHM=1,5cm) are emitted from appointlocated 100cm from the target from the void of the first sphere and are accelerated towards the target in the direction of the Z axis of propagation.

This geometry modeled by the flair interface [9] will be used to evaluate the dose deposition in depth of carbon and helium ions of the above mentioned energy. In a simplified way, the absorbed dose is the energy given up by an irradiation to a given volume in relation to the mass of the irradiated volume and has for unit the Gray (Gy)[10]. 1Gy=1d/kg

$$D= dE/dm$$

With dE average energy given by the irradiation to the volume, and dm the mass of the irradiated volume.

The simulation was performed under the hadron therapy option. Only the primary doses have been evaluated taking into account the electromagnetic and nuclear interactions which are the fundamental processes of dose deposition of ionizing radiation in the medium.

Results of the simulation will be presented as follows:

In a first position the deposition profiles of depth dose of the above mentioned carbon ions of energy will be presented, in a second position the results of the helium ions of the same energy will be drawn up and a summary on the position of the peak of both particles and the deposited dose willbe drawn up.

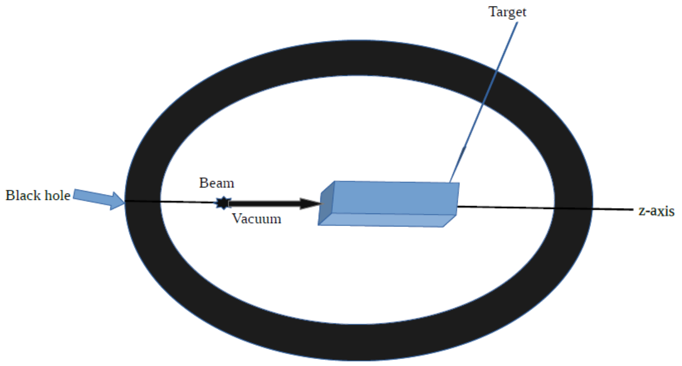

Figure 1: geometry of study modeled with Flair

Table 1: Summary of the characteristics of the modeled geometry

Elements to be described	characteristics
Target	Rectangular parallelepiped: Xmin=-10 ;Xmax=10 (RPP) Ymin=-10 ; Ymax=10 Zmin=0,0 ; Zmax=40
Vacuum	Sphere radius r=10000cm
Black hole	Sphere radius R=100000cm
Beam (carbon; helium)	Direction: propagation Z axis distance Beam-target =100cm intensity: 100, 200, 300, 400MeV

Results and discussions

The curves in Figure 3 represent the depth dose deposition of carbon ions in water phantom. In (a) we have the dose deposition of the 100MeV intensity beam, in (b) the 200MeV energy beam, in (C) 300MeV, in (d) 400MeV. And figure 4 represents the dose deposited by the helium beams of 100MeV in (a), 200MeV in (b), 300MeV in (c) and 400MeV in (d).
The analysis of the dose deposition curves obtained by the two particles (carbon and helium) are characterized by a relatively low entry dose whatever the intensity of the beam and a concentration of energy at the end of the path contrary to the photon x and ɣ. This accumulation of dose at the endof the path is represented on the curves by a peak known as the Bragg peak [11].
The results of this study reveal the possible delocalization of the Bragg peak by modifying the intensity of the incident beam. Thus, in a homogeneous medium such as the human body, where 70% of the tissues are composed of water, a carbon beam of 100MeV, 200MeV, 300MeV and 400MeV would allow the treatment of tumors located respectively at 2.5cm, 8.6cm, 16.2cm and 27.4cm in depth (Figure 3), whereas for the same intensity, a helium beam would only allow the treatment of tumors located at 0.6cm, 2.1cm, 4.7cm and 7.8cm in depth (Figure 4). For a tumor located at 8.6cm depth, a center using carbon ion beams will need energy of 200MeV while the one using helium ions will use an intensity of 425MeV and will deposit less dose than carbon ionsas shown in figure 2

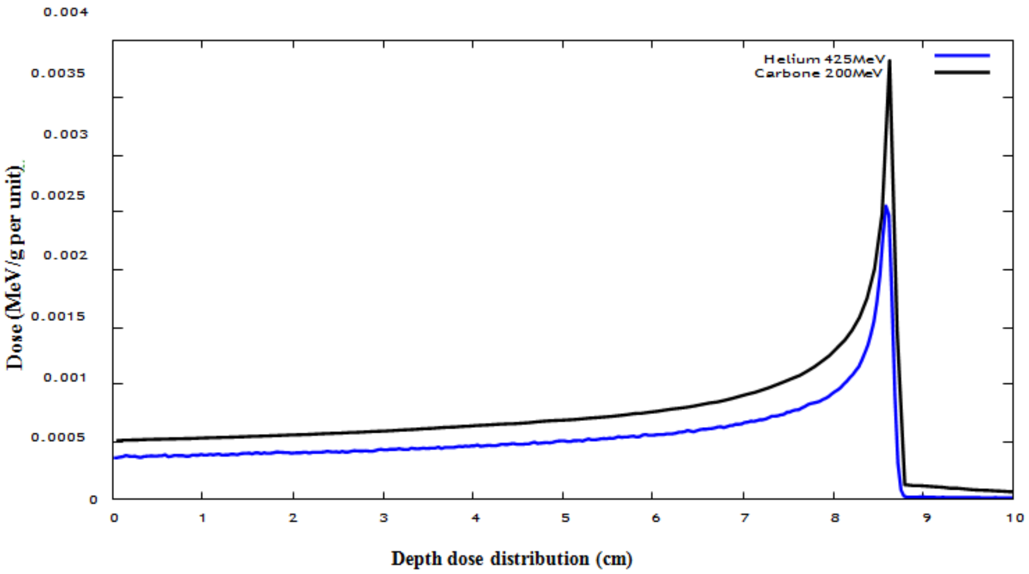

Figure 2: Depth dose distributions of carbon beam of 200 MeV and helium beam of 425 MeV water calculated using FLUKA MC

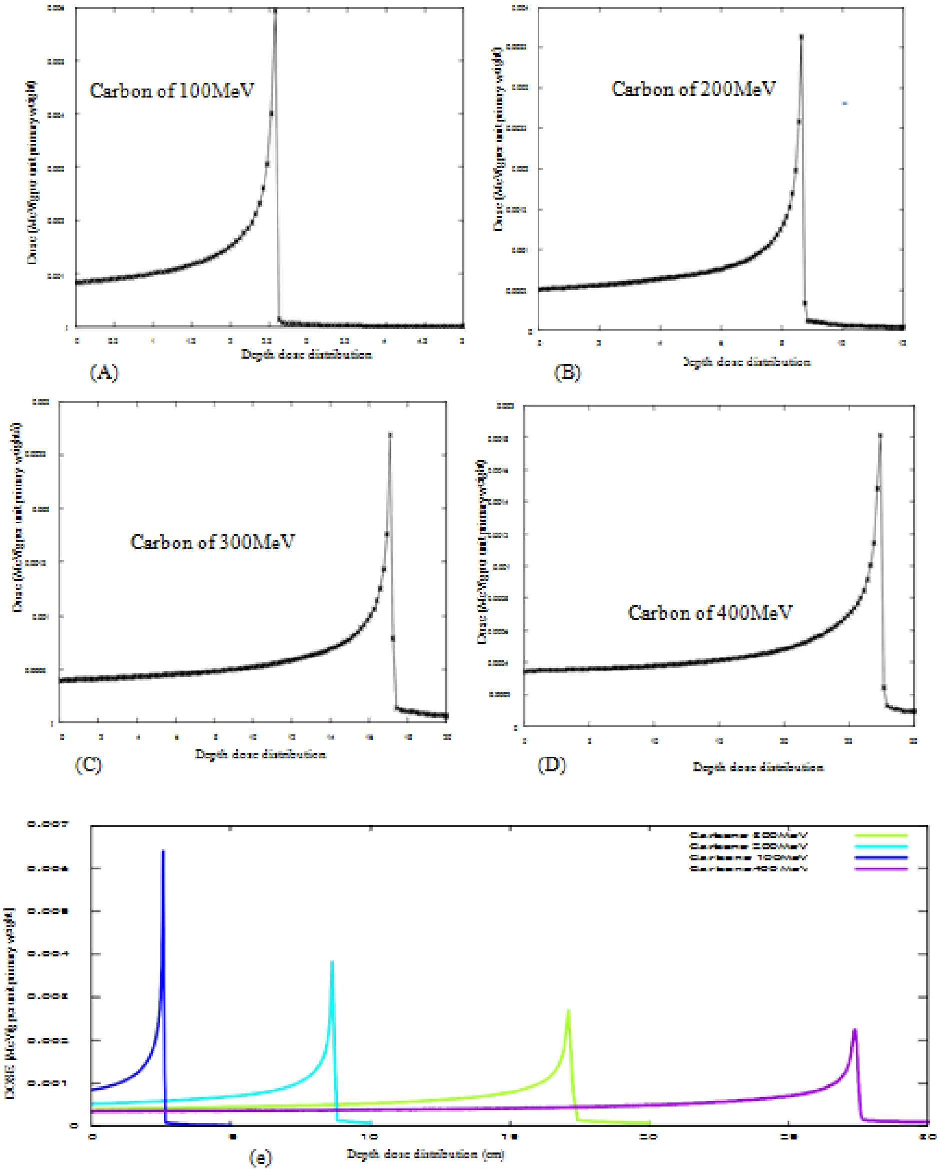

Figure 3: Depth dose distributions of carbone beam of different energy in water calculated using FLUKA MC Code

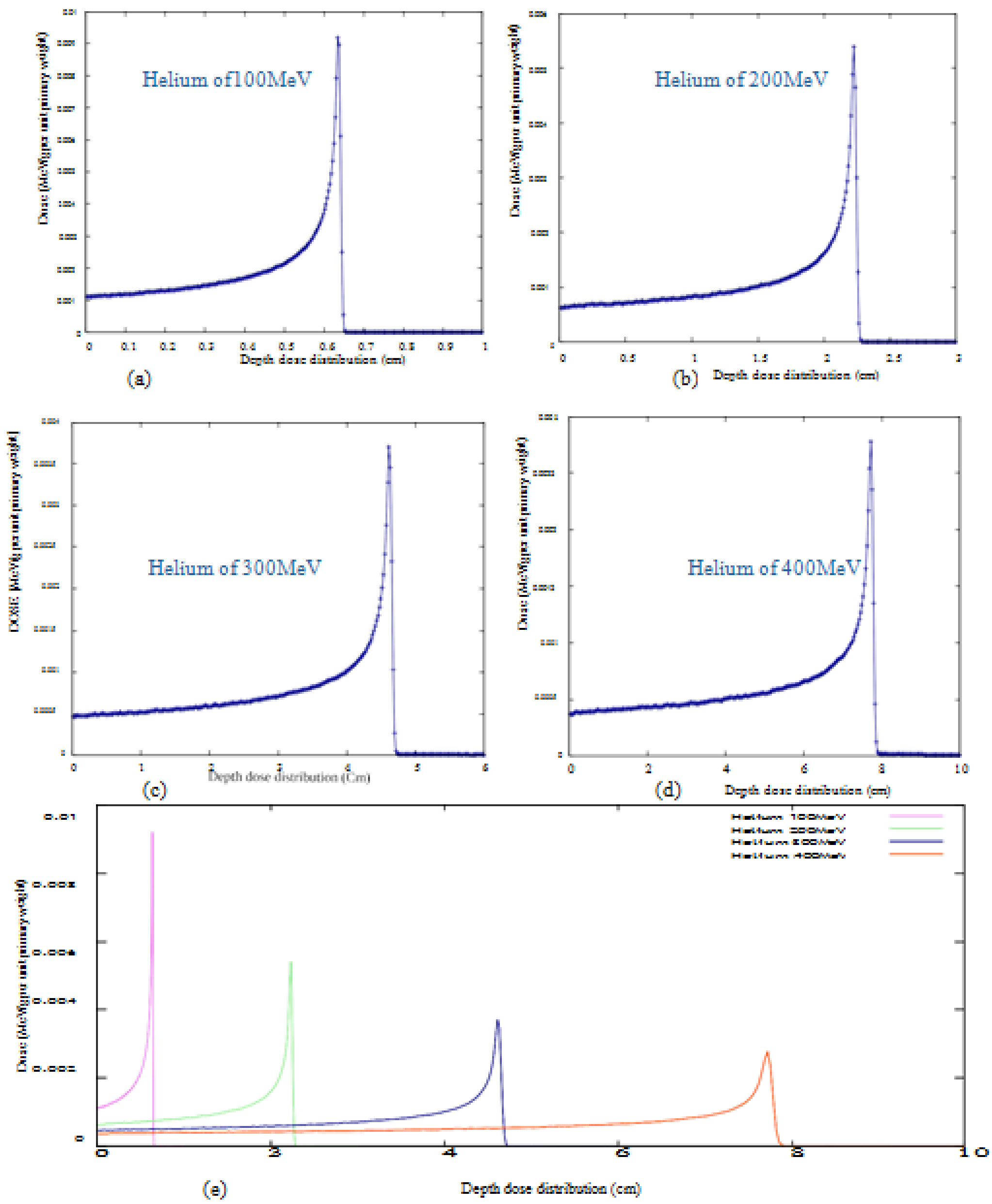

Figure 4: Depth dose distributions of helium beam of different energy in water calculated using FLUKA MC Code

Table 2: Summary of the Bragg peak position and the deposited dose as a function of the different energies

Type of particle		Intensity in MeV			
		100	200	300	400
Carbon	Peak position (Cm)	2,5	8,6	16,2	27,4
	Deposited dose(MeV/g/upw)	0,0061	0,0037	0,0027	0,0018
Helium	Peak position (Cm)	0,6	2,1	4,7	7,8
	Deposited dose (MeV/g/upw)	0,0091	0,0055	0,0037	0,0025

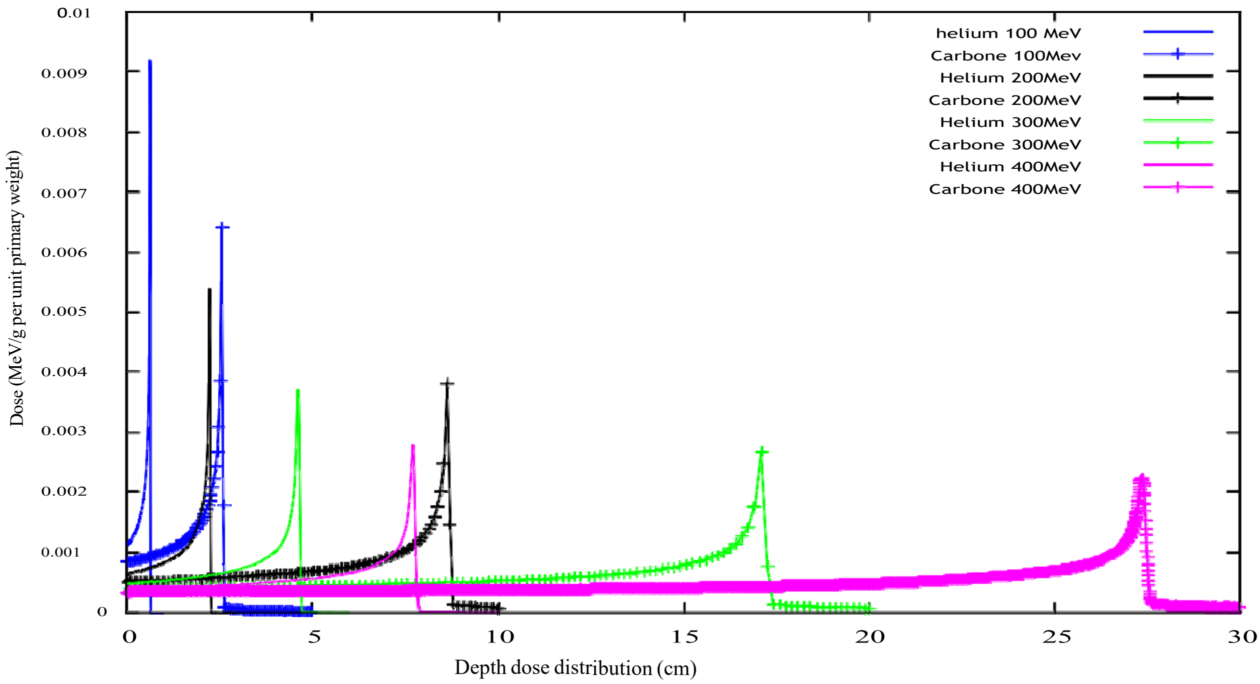

Figure 5: Depth dose distributions of helium and carbon beam of different energy in water calculated using FLUKA Code

The analysis of the simulation results shows points of convergence and divergence of the two types of particles.

Points of convergence:

- High is the beam intensity, low is the input dose

- The more energetic the particle, the greater the depth of dose deposition (table 2)

- The less the particle reaches the depths, the more it deposits dose (the more the particle crosses thematter, the more it undergoes interaction, the more it loses energy) (table 2)
- The FWHM of the two particles (carbon and helium) are identical:

- At the same energy, carbon ions are more penetrating than helium ions (figure 5)
-At the same energy, carbon ions deposit less dose than helium ions (table 2)

- Dose deposition curve cancellation just after the Bragg peak for helium

- Prolongation of the dose curve after the peak for carbon (fragmentation tail) (figure2) the results ofour study agree with those found by M. Yjjou [11], Valle [12] and Henriquet [13].
Contrary to the helium ion dose deposition curve whose dose cancels just a few mm after the Bragg peak (absence of the fragmentation tail), the carbon ion curves are characterized by a prolongation of the dose deposition curve after the peak, known as the fragmentation tail. It increases with the intensity and would be responsible for the additional doses received by the healthy tissues located behind the tumor and witnesses the emission of secondary particles resulting from the nuclear interaction between the incident particle and the matter. As the energy increases, the coulomb barrier can be crossed, thus multiplying the interactions and the emission of secondary particles [15]. In addition to the additional doses to healthy tissues, the secondary particles emitted by thecarbon ion beams are used to follow the dose deposition in the patient during radiotherapy sessions by PET (Positron emission tomography). Helium ions being

less penetrating than carbon ions at the same energy but depositing more dose than carbon ions can be used for less deep tumors.

Conclusion

The present investigation has investigated the behavior of the interaction between heavy ions and medium at different energies. Regarding obtained results, we can affirm that carbon and helium ions present almost the same characteristics of dose deposition in depth except for some small differences (presence of fragmentation tail for carbon ions and differences of dose deposition in depth at the same intensity) which can be compensated or taken advantage of for other purposes (dose deposition monitoring by PET) by the technology. Thus, one wonders about the abandonmentof helium in the sphere of hadron therapy. But the effect of radiation is not limited to the physical dose deposited in the matter, other complementary work must be carried out to confirm or deny the return of ions in the world of charged particle radiotherapy.

References

[1] R. R. Wilson et al., «Radiological use of fast proton», Radiology,vol.47, n°.11, p.487-491,1946.

[2] Buffon G. «Essai d'arithmetique supplement à la naturelle».

[3] A. Didi et al., «Helium ion therapy compared to protons therapy using MCNP monte Carlocode», physics AUC, vol.29, p.77-83, 2019.

[4] A. Ferrari et al., A multi-particle transport code, CERN 2005-10 (2005), INFN/TC05/11,SLAC-R-773.

[5] Agostonelli A. et al., (Geant4 collaboration). Geant4: simulation toolkit. Nucl. Instrum. Methods, vol. A 506 p.250-303, 2003.

[6] A. MCNP6, MCNP (2014) X-6 Monte Carlo Team, N-Particle Transport Code System IncludingMCNP6.1, and Data Libraries, MCNP6 User's Manual, Code Version 6.1.1beta, LA-CP-14-00745.

[7] Niita K. et al., PHITS: Particle and heavy ion transport code system, version 2.23, JAEA- DATA/Code 2010-022. Japan: Japan Atomic Energy Agency; 2010.

[8] Vlachoudis, V. (2009) Computational methods & reactor physics (M&C 2009), technical report.

[9] Didi A.et al., «Calculate primary and secondary dose in proton therapy using 200 and 250MeV proton energy», Moscow university physics bulletin, 2019.

[10] W. H. Bragg et al., Philos. Mag. S6, 726 (1904).

[11] Yjjou M. et al., «A comparison based on the calculation of some hadron doses in addition tothe secondary neutron fluence using the FLUKA Monte Carlo code», Int. J. Nuclear Energy Science and Technology, vol.14, no°4 p.302-309, 2020.

[12] Valle, S. M., «Hélium ion beam for eye treatment», Master's thesis, 2013.

[13] Henriquet P., «Etude de l'émission de particules chargées secondaires dans l'optique d'un monitorage faisceau et de dosimétrie en ligne en hadronthérapie, PhD thesis, Université Claude Bernard-Lyon I, 2012.

[14] Laitano et al., «Effects of nuclear interactions on energy and stopping power in proton beam dosimetry nuclear instruments & methods in physics research section A» vol.376, p.466- 476, 1996.

[15] Medin, «Study of clinical Proton dosimetry using Monte Carlo simulation and experimental techniques» thèse de doctorat, Université de Stockholm, 1997.