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An accurate model for the computation of the dose of protons in water

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ABSTRACT

Purpose: The accurate and fast calculation of the dose in proton radiation therapy is an essential ingredient for successful treatments. We propose a novel approach with a minimal number of parameters.
Methods: The approach is based on the exact calculation of the electromagnetic part of the interaction, namely the Molière theory of the multiple Coulomb scattering for the transversal 1D projection and the Bethe-Bloch formula for the longitudinal stopping power profile, including a gaussian energy straggling. To this e.m. contribution the nuclear proton-nucleus interaction is added with a simple two-parameter model. Then, the non gaussian lateral profile is used to calculate the radial dose distribution with a method that assumes the cylindrical symmetry of the distribution.
Results: The results, obtained with a fast C++ based computational code called **MONET** (MOdel of ioN dosE for Therapy), are in very good agreement with the FLUKA MC code, within a few percent in the worst case.
Conclusions: This study provides a new tool for fast dose calculation or verification, possibly for clinical use.

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1. Introduction

For the accurate dose calculation in proton radiation therapy the traditional Monte Carlo (MC) simulation approach is currently considered to be the best method [1–3], but its clinical application is limited by the long computation time.

Alternative approaches are based on accurate and long time consuming pre-calculations of many MC 3D profiles, that permit a reasonably fast computation in the clinical practice, but at the expense of a large memory usage.

Other approaches are based on phenomenological parameterizations that attempt to describe the electromagnetic (e.m.) and hadronic physics of the interaction of the protons in the patient's tissues: often these models are Gaussian approximations of the lateral profiles in one dimension and the final 2D dose profiles are obtained by factorization. These models are less accurate than MC calculations and often depend on a high number of parameters, making difficult a simple and intuitive physical interpretation.

Here we propose a model that has an accuracy comparable with that of MC calculations, based on our previous work on the calculation of the lateral beam profile with the Molière theory of multiple Coulomb scattering ([4], summarized in Section 2.1) and on the Bethe-Bloch formula for the longitudinal stopping power profile, including a gaussian energy straggling (Section 2.2). To this e.m. contribution the nuclear proton-nucleus interaction is added with a simple model that requires two parameters to be adjusted at any depth for the lateral profile and two parameters only at each energy for the longitudinal profile (Section 2.2.3).

Carrying the analytical calculations in one dimension for the lateral distribution allows a simple inclusions of beam and phase space effects through the one dimensional convolution.

Then, this non gaussian lateral profile is used to calculate the 2D radial dose distribution with a method that assumes the cylindrical symmetry of the beam (Section 2.1.1).

In this study we have evaluated the dose of proton beams only for water: due to the very general validity of most of the used equations for other materials, we foresee the extension of this model also to all media of interest in hadrontherapy. The only inputs required for the calculation are the initial beam energy and lateral profile, either Gaussian or arbitrary from a phase space file. The data that are necessary to calculate a database for fast clinical applications are only two parameters at each energy for the nuclear component of the longitudinal Bragg curve and two parameters at any energy and depth for the profile of the nuclear part of the lateral distribution.

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The model is tunable to any realistic situation and has been tested in conditions similar to those of the HIT and CNAO centers (Section 3).

2. Methods and materials

2.1. Lateral profile

The lateral dose profile is produced by the combination of two processes, the electromagnetic multiple Coulomb scattering and the nuclear interactions. The scattering of charged particles in a medium is described by the Molière theory, which allows to calculate the deflections of the primary particle trajectories from the original direction in terms of a spatial angle θ. In the previous paper [4] we have presented a numerical model to account for these effects and to calculate both the angular and the lateral displacement distributions with the expression [1]:

$$f_x(x) = W_p f_M(x) + (1 - W_p)\frac{t(x)}{\int t(u)\mathrm{d}u} \tag{1}$$

where $f_M(x)$ is Molière distribution (on the x projection, a similar expression stands also for the y projection), W_p is the weight of the e.m. interactions and $(1 - W_p)$ is the weight of the nuclear contribution. These weights are computed with analytical formulas ([5], Eq. (54)) already validated with experimental data. In this work we only consider the decrease in fluence of the primary protons and we include the effects of secondary protons and of recoil ions that are produced in the target fragmentation in the best fit of the distribution tails, as explained in the following. The Molière distribution is given by: [2]

$$f_M(x) = \frac{1}{\pi\chi_c\delta}\int_0^\infty \cos\left(\frac{x\eta}{\chi_c\delta}\right)\exp\left[-\frac{\eta^2}{4}\left(b - \ln\frac{\eta^2}{4}\right)\right]\mathrm{d}\eta, \tag{2}$$

where $b = \ln(\chi_c^2/\chi_\alpha^2) - 0.154432$, χ_α and χ_c are the standard Molière parameters taking into account mixtures, compounds and the energy loss during the slowing-down process in the absorber ([4], Eqs. (7, A19, A21)). An example of the projected lateral distribution obtained with this model is compared with the FLUKA ([3,1]) predictions and with experimental data in [4] (Fig. 4).

The energy dependence of the Molière parameters has been calculated through the formula [6,7]:

$$p(z)^2\beta(z)^2 = p^2\beta^2\left(1 - \frac{z}{R}\right)^k, \tag{3}$$

where R is the CSDA range for the incident particle of momentum p and velocity β ($c = 1$), $p(z)$ and $\beta(z)$ are momentum and velocity of the particle at the depth z and $k = 1.07$ for water. This formula is accurate enough (better than 2%) for all the therapeutic energies in water, as shown by Ulmer [8] where the CSDA formula is derived. This form for energy loss is particularly useful in Molière theory, where the parameter χ_c, which determines the root mean square of the distribution, can be expressed as [9,4]:

$$\chi_c^2 = \chi_w^2\frac{1}{p^2\beta^2}\int_0^z \frac{1}{(1 - t/R)^k}\mathrm{d}t = \chi_w^2\frac{R[(1 - z/R)^{1-k} - 1]}{p^2\beta^2(k - 1)}. \tag{4}$$

where χ_w^2 contains the energy independent terms. The scale factor δ in Eq. (2) allows the passage from the angular to the spatial distribution observed after the passage of a thickness x and is obtained by adding in quadrature all the squares of the deviations at different thicknesses divided by χ_c from Eq. (4) ([4], Eq. (10)):

$$\delta^2 = \int_0^z \frac{(z - t)^2}{(1 - t/R)^k}\mathrm{d}t \Big/ \int_0^z \frac{1}{(1 - t/R)^k}\mathrm{d}t. \tag{5}$$

In this way the root mean square of the lateral distribution is $x_{RMS} = \delta\chi_c\sqrt{B}/\sqrt{2}$ and the substitution of the term χ_c with the term $\delta\chi_c$ in Eq. (2) transforms the distribution of the projected angle in that of the projected displacement. The presence of the B term, that depends logarithmically on the thickness, takes into account that the two successive layers act in a dependent manner, since the second layer receives trajectories deflected by the first one. This property is sometime called as nonlocality [10].

The lateral displacement distribution of Eq. (2) includes only the effect of e.m. interactions based on the physics of multiple scattering.

The traditional approach in particle therapy is to use the so called Fermi-Eyges theory: the rationale behind this dates back to the first applications with electron beams and is still applied with hadrons, as explained in [10]. This theory is essentially a Gaussian approximation of the core and is not able to reproduce the distribution tails: nevertheless it is customary to add these effects as further approximate parameterizations called improperly nuclear "halo", "aura" and "spray" to fully describe both the electromagnetic and nuclear scattering [11,12]. Our approach instead, as explained in [4], is based on the description of the lateral displacement by the Molière theory corrected with the scale factor of Eq. (5). This approach is able to give better accuracy than the integration of the Fermi-Eyges distribution to obtain the marginal Gaussian distribution of the lateral displacement.

As an example the difference between these two complementary approaches is summarized for e.m. interactions in Fig. 1, in comparison with the FLUKA code.

This code, in addition of being used for treatment plans verification at both european hadrontherapy centers HIT and CNAO, is the only one to treat multiple scattering in a very detailed way [13], using the Molière theory well within its limits of validity for what concerns the calculations of the step size during the simulation [14]. For this reason in our simulations the step size is always calculated by FLUKA and is never below the critical values of 3–5

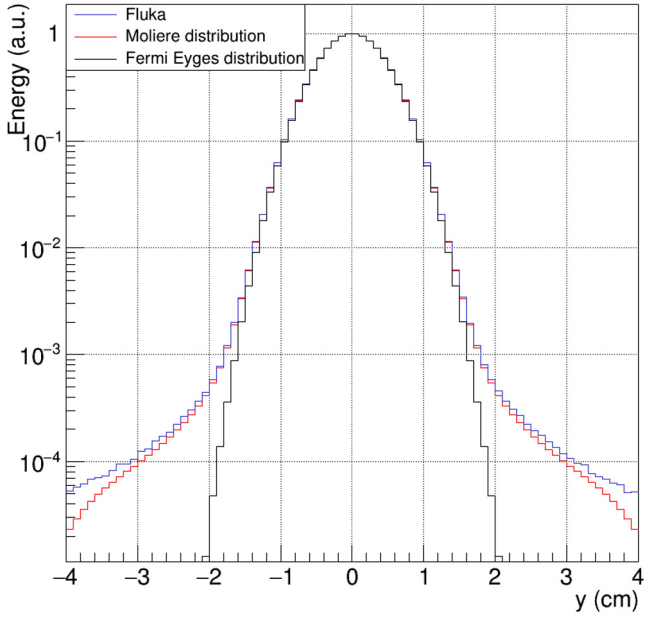

Fig. 1. Lateral distributions from e.m. only interactions in Molière and Fermi-Eyges theories for an initial gaussian beam of E = 150 MeV protons at a depth of 11 cm in water. The comparison with FLUKA is done considering only e.m. interactions.

[1] In the following we refer to a cartesian coordinates system with the beam directed along the positive z axis and with the xy plane as the transverse plane.

[2] Here we correct a misprint in Eq. (12) and (A11) of [4], where the factor $\eta\mathrm{d}\eta$ should be corrected in $\mathrm{d}\eta$

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