Title page

Stopping power for particle therapy: the generic library libdEdx and clinically relevant stopping-power ratios for light ions

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Abstract

Purpose:

Stopping-power data enter at a number of different places in particle therapy and their uncertainties have a direct impact on the accuracy of the therapy, e.g., in treatment planning. Furthermore, for clinical quality assurance, the particle beam stopping-power ratios (STPR) have to be known accurately for dosimetry.

Methodological developments and calculations:

An open-source computer library called libdEdx (library for energy loss per unit path length, d*E*/d*x*, calculations) is developed, providing stopping-power data from data tables and computer programs as well as a stopping-power formula comprising a large list of target materials. Calculations of STPR in the case of spread-out Bragg-peaks (SOBP) are performed with the Monte Carlo transportation code SHIELD-HIT (SHIELD-Heavy Ion Transport) using different ions relevant for particle therapy.

Results:

For SOBP the water-to-air STPR depends on the residual range and is qualitatively very similar for different ions; however, small quantitative differences exist between the considered ion species.

Conclusions:

libdEdx allows for a convenient and efficient treatment of stopping powers in numerical applications. It can be applied to estimate the dependence on the accuracy of the stopping power and to provide data for an extended number of target materials. The STPR for SOBP for different ions are found to be qualitatively the same which may allow for an analytical description valid for all ions.

1. Introduction

In particle therapy, stopping-power data are relevant for a number of different quantities such as range of particles, depth-dose distribution, stopping-power ratios for dosimetry, and relative biological effectiveness. Accordingly, the accuracy of position and dose which can be achieved in particle therapy depends on the accuracy of the available stopping power. However, in Monte Carlo (MC) simulations different sources of stopping-power data are in use, e.g., International Commission on Radiation Units & Measurements (ICRU) reports 37, 49, and 73, MSTAR (program calculating electronic stopping powers for heavy ions), Stopping and Range of Ions in Matter (SRIM) (ICRU 1984, ICRU 1993, ICRU 2005, Paul and Schinner 2010, Ziegler 2010) or various implementations of stopping formulas including Bethe theories (Bethe 1930, Bethe 1932) using appropriate mean excitation energies (*I*-value) (ICRU 1984, ICRU 1993, ICRU 2005). In general the data provided by these stopping-power sources differ among each other. Therefore, the results of calculations which use stopping-power data as input as well as their accuracy depend on the chosen source and its uncertainties. It should be mentioned, that even the stopping-power data recommended by ICRU (ICRU 1984, ICRU 1993, ICRU 2005) are inconsistent since the description of a target material may depend on the ion species.

Consequently, it would be desirable to have an easy access to a number of different stopping-power data sets readily available. It might be directly used to study the dependence of results obtained with a MC simulation on the stopping-power data used as input. Having this in mind, certain requirements for a possible multipurpose tool providing stopping-power data are specified, including free availability, high performance and accuracy as well as an easy incorporation in existing codes. In an attempt to meet the specified requirements, we have developed the numerical stopping-power library called *libdEdx* (library for energy loss per unit path length, d*E*/d*x*, calculations). However, even apart from the aspects of performance and consistency libdEdx might be considered as a convenient and unique tool providing stopping-power data for various applications.

A quantity directly influenced by the stopping power is the stopping-power ratio (STPR). The STPR for water-to-air is of relevance in dosimetry with air-filled ionization chambers which are routinely used at particle therapy centers for quality assurance of the delivered beam in water phantoms. Thereby, the STPR enters in the dose determination as a correction factor which converts the measured dose in air to the absorbed dose in the water phantom. Actually, a constant value of 1.13 is recommended by the International Atomic Energy Agency (IAEA) for ions heavier than protons in the Technical Reports Series No. 398 (TRS-398) (IAEA 2000) with an assumed uncertainty of 2% influencing directly the uncertainty in quality assurance.

Consequently, STPR have recently been actively studied for monoenergetic carbon beams (Henkner et al. 2009, Geithner et al. 2006) and a large variety of different monoenergetic ions as well as spread-out Bragg-peaks (SOBP) for carbon ions (Lühr et al. 2011). However, the dependence of STPR on the ion species has not been studied so far for SOBP and is investigated here. An emphasis is put on STPR for different clinically relevant light ions from protons up to oxygen.

2. Methods

2.1 Development of a generic stopping-power library libdEdx

We have implemented the computer library libdEdx in a completely open-source project which is available online (Toftegaard et al. 2011). The library consists of platform-independent routines written in the programming language C. By now, libdEdx is able to reproduce the stopping-power data of the stopping-power and range tables (STAR) for electrons, protons, and helium ions, provided by the three programs ESTAR, PSTAR, and ASTAR, respectively (Berger et al. 2011), corresponding to ICRU reports 37 and 49 for electrons, protons, and alpha particles, respectively. For ions heavier than helium, libdEdx provides data of the tables in ICRU report 73 and of the program MSTAR. Values by libdEdx may differ due to rounding errors at most by unity from the last significant digit provided by the original data source which is usually smaller than 0.01%. Additionally, a Bethe stopping formula (ICRU 1993, Bethe 1930, Bethe 1932) is implemented with a low-energy extension as suggested by Lindhard and Scharff (1961). The range of applicability of this formula is in principle neither limited to a selection of ions nor to specific target materials.

Furthermore, the library includes the full list of material-composition data as provided by ICRU which specifies over 250 materials. In libdEdx, these material-composition data can be used in combination with all implemented stopping-power data. In the case that a chosen source of stopping-power data originally does not provide data for the material under consideration two options are provided by libdEdx. First, Bragg's additivity rule as described in (ICRU 1993) together with the material-composition data can be used with available stopping-power data of the constituent atoms. Second, the Bethe stopping formula can be used either with a mean excitation energy I given in the material-composition data or one which is specified by the user.

libdEdx provides two different modes of application. First, there is an easy to use default mode with convenient default settings which requires only minimal knowledge on stopping powers by the user. Second, there are routines for fast look-up of stopping-power data with high efficiency which provide about 15 million stopping-power values per second on one processor. The latter routines can be integrated in simulation programs such as MC codes where about a thousand calls of a stopping-power routine per primary particle can be expected in clinically relevant simulations. At this moment a comprehensive documentation of the library is in preparation which may contain detailed descriptions of the provided routines, a decision tree, and several small examples for applications.

2.2 Stopping-power ratios for SOBP

The STPR is defined according to the TRS-398 protocol (IAEA 2000) and is implemented in the recent version 10A of the Monte Carlo transportation code SHIELD-HIT (SHIELD-Heavy Ion Transport) (Gudowska et al. 2004, Hansen et al. 2011, Sobolevsky 2011) as described in detail in (Lühr et al. 2011). The influence of the secondary particles is taken into account using the full particle energy spectra of all contributing ions. The stopping power data used by the MC program are provided by the Bethe equation implemented in libdEdx, as described in Sec. 2.1, employing the I-values 78 eV and 82.8 eV for water and air, respectively. These values are recommended by ICRU (2005). The physical dose optimization of the SOBP for the different ions performed in this work is similar to what was done by Bassler et al. (2010).

3. Results

3.1 libdEdx

Figure1

Figure2

To illustrate possible applications of libdEdx, two examples are presented in Figures 1 and 2. Figure 1 shows depth-dose distributions of SOBP for oxygen ions in water calculated with the recent version SHIELD-HIT10A using different stopping-power data provided by libdEdx. While the qualitative behavior of the depth-dose distribution does not change much, the distal edge of the SOBP differs up to 2 mm using either the original ICRU data (ICRU 73_old) or the recently revised *I*-value (Bethe 78 eV) from the erratum of ICRU 73. Figure 2 shows the application of the material-composition data for the case of the material “tissue soft” as specified by ICRU. For this material no data are provided by PSTAR, ASTAR (i.e. ICRU 49), ICRU73 or MSTAR. Here, stopping-power data were produced with libdEdx using Bragg's additivity rule together with MSTAR data of the constituting atoms for hydrogen, helium, carbon, oxygen, and argon (H, He, C, O, and Ar, respectively) ions.

3.2 Dependence of STPR for SOBP on the ion species

Figure3

Figure 3 shows the water-to-air STPR as a function of the residual range R_{res} in water for SOBP of the ions H, He, C, and O which are all available in particle therapy centers such as at the Heidelberg Ion-Beam Therapy Center (HIT), Heidelberg, Germany. An example of the depth-dose distributions for the

SOBP is displayed in Figure 1 for oxygen ions denoted as “Bethe 78 eV”. It can be observed that the qualitative behavior of the water-to-air STPR curve as a function of R_{res} is the same for all ions studied here. Small differences in the absolute values of the STPR curves can be observed among the studied ions being below 0.1% in the SOBP region ($0 < R_{res} < 50$ mm). The deviation of the STPR from the fixed value 1.13 recommended by IAEA is of the order of 1% for 10 mm $< R_{res}$.

4. Discussion

The generic open-source library libdEdx accurately reproduces in a convenient and efficient way stopping-power data from a number of stopping-power tables, programs and a Bethe stopping formula. One of its distinct features is that for more than 250 materials, specified by ICRU, stopping-power data can be provided, even for some materials for which stopping-power data are not otherwise available. Apart from a simple look-up of data, libdEdx can be expected to be highly valuable for the purpose of a convenient comparison of MC simulations performed with different stopping-power data. Thereby, the resulting uncertainties originating from the stopping-power data can be estimated as it was done in (Lühr et al. 2011). While the basic functionality of libdEdx and a technical framework are provided, its open-source framework enables possible extensions with new stopping-power tables, algorithms and improved stopping power formulas.

The water-to-air STPR for SOBP with H, He, C, and O ions depend mainly on the residual range R_{res}. Qualitatively, the STPR does not differ significantly for the different ion beams used in this study. Therefore, the conclusions concerning STPR for SOBP of carbon ions in (Lühr et al. 2011) are to a large extent also valid for other ion species. There, a fit of the STPR as function of R_{res} was proposed. The fit parameters, however, seem to be slightly dependent on the ion species. It would be of practical use to establish a simple analytical expression of STPR for SOBP as function of R_{res} similar to what was proposed for pristine peaks (Lühr et al. 2011) replacing the purely empirical fitting. However, a general expression for SOBP is more difficult to obtain since the optimization of SOBP is not unique.

The small quantitative differences among the STPR for different ions can be explained by the differences of their energies at a given R_{res} rather than ion-specific properties. For energies relevant for particle therapy higher velocities lead to smaller STPR (Lühr et al. 2011). While the STPR curves for H and He ions are basically the same until the distal end of the SOBP, differences beyond the SOBP (R_{res}

< 0) are expected due to different spectra of secondary particles but also due to a differences in the definition of the practical range for protons compared to heavier ions (IAEA 2000, Lühr et al. 2011). With the results obtained in this study together with those from (Lühr et al. 2011), we finally conclude that for pristine peaks as well as for SOBP only small quantitative differences can be observed for STPR curves for different ions.

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Declaration of Interest

The authors report no declarations of interest.

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Figures

The description of the figures has the following format:

“**Figure name in manuscript**”: “name of figure file .pdf”

Caption text

Figure1: *Figure1.pdf*

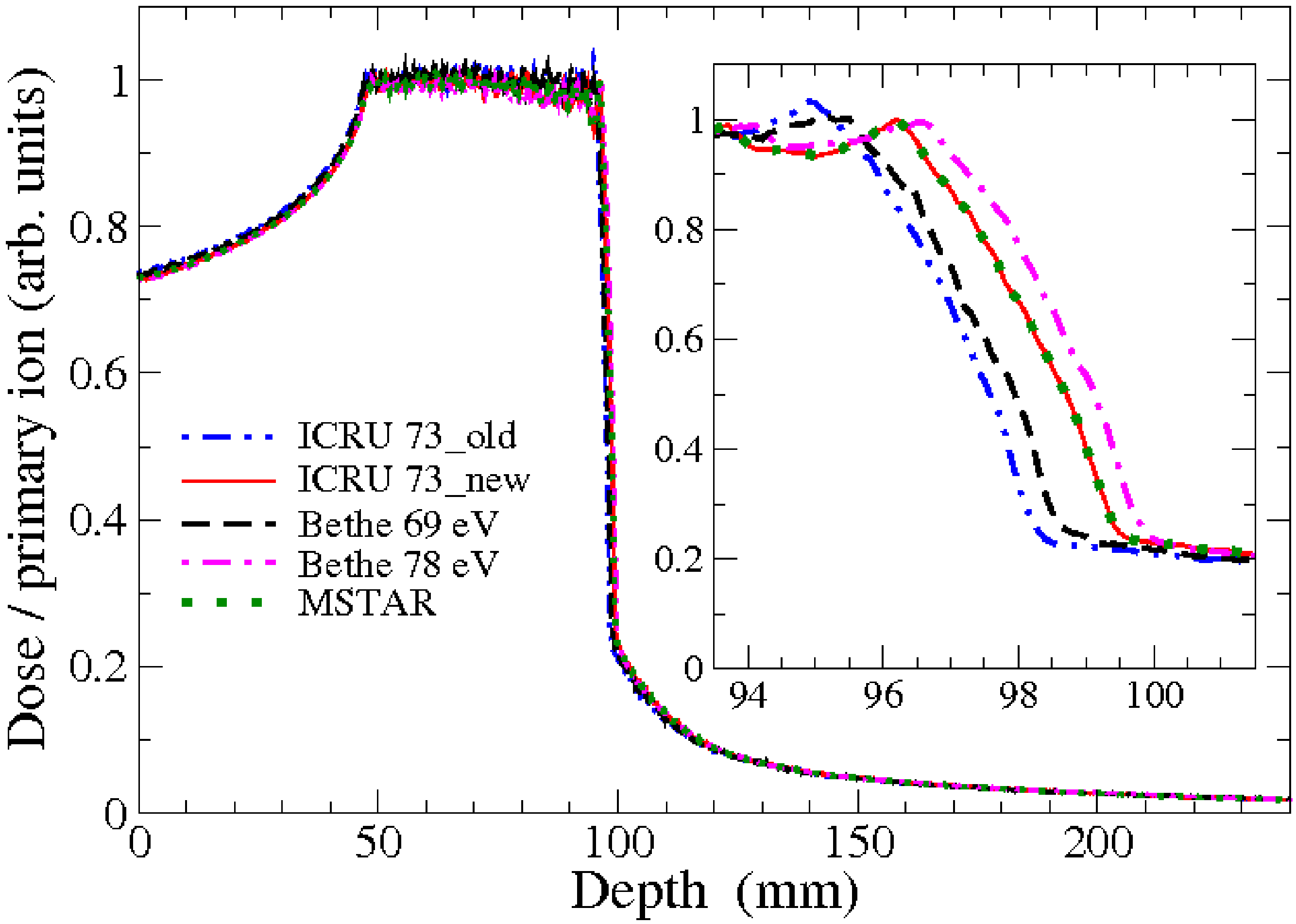
Depth-dose distribution of a SOBP for oxygen ions on water obtained with SHIELD-HIT using different stopping-power data. The distal end of the SOBP is shown enlarged in the inset.

Figure2: *Figure2.pdf*

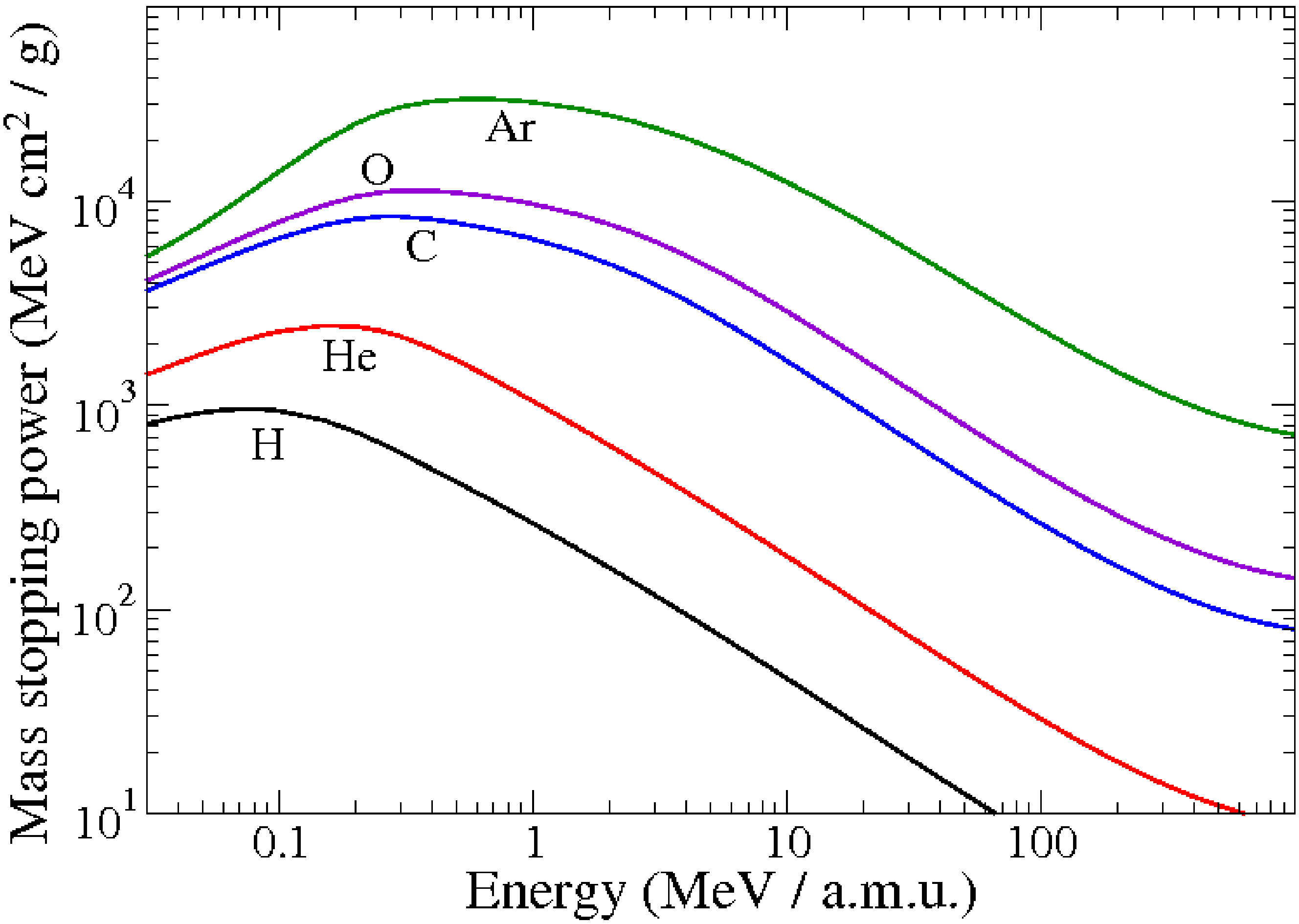
Mass stopping powers as function of energy for the ions H, He, C, O, and Ar in the material "tissue soft" which is defined by ICRU (1984). The data were determined by libdEdx using Bragg's additivity rule with MSTAR (Paul and Schinner 2010) data which do not provide data for this material directly.

Figure3: *Figure3.pdf*

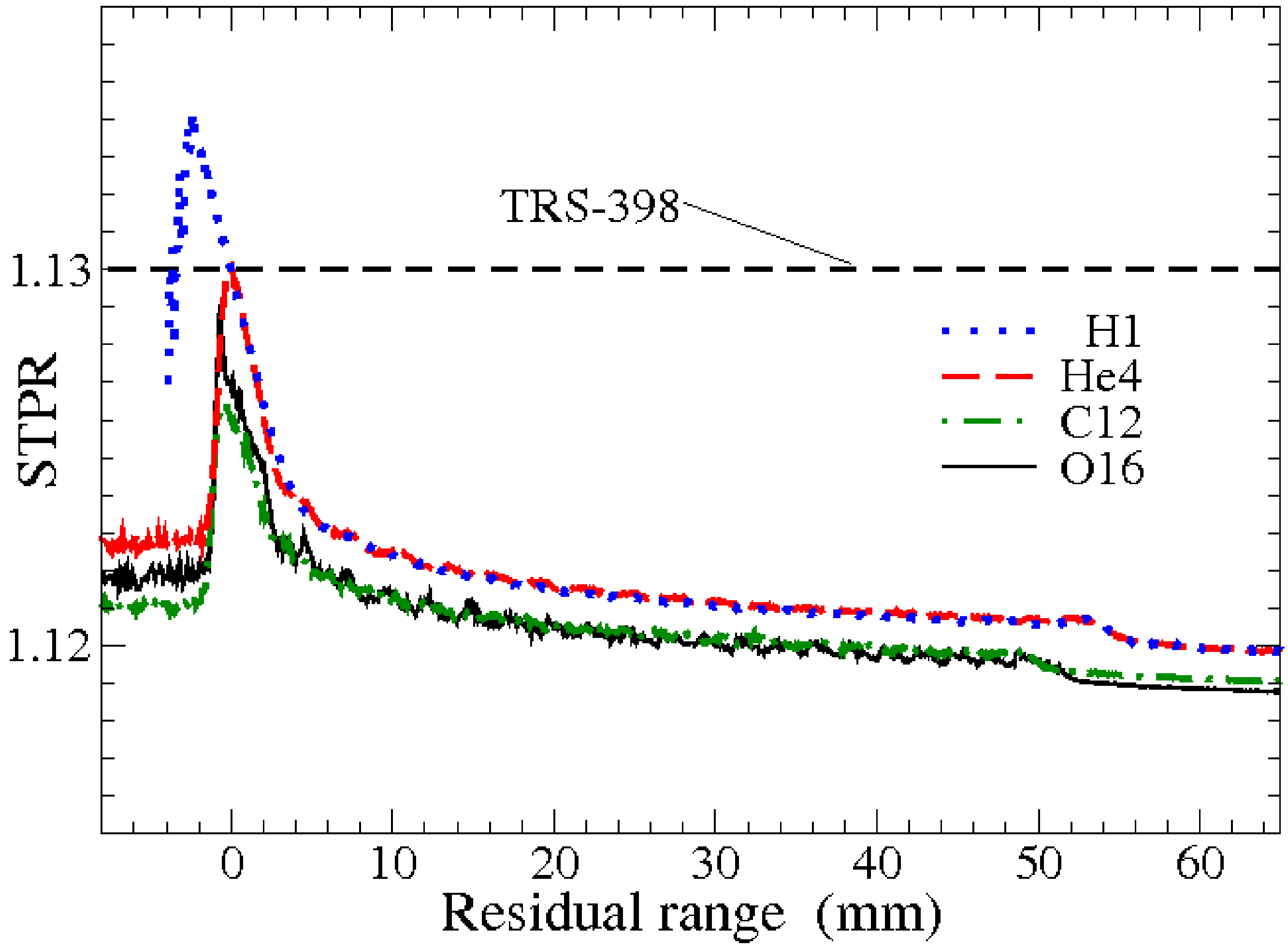
Water-to-air stopping-power ratio as function of the residual range for SOBP obtained with SHIELD-HIT. The results for H, He, C, and O ions are compared. Also given is the value 1.13 recommended in TRS-398 (IAEA 2000).



Dose / primary ion (arb. units)
Depth (mm)
ICRU 73_old
ICRU 73_new
Bethe 69 eV
Bethe 78 eV
MSTAR



Mass stopping power (MeV cm^2 / g)
Energy (MeV / a.m.u.)
10^1
10^2
10^3
10^4
0.1
1
10
100
Ar
O
C
He
H



TRS-398
H1
He4
C12
O16
STPR
1.13
1.12
0
10
20
30
40
50
60
Residual range (mm)