Feasibility study of the proton yield from the reaction D(3He,p)4He as a possible tool for radiotherapy treatment

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Abstract. Recent achievements in proton and carbon ions therapy have shown the importance of the hadron therapy methods. Aiming at radiotherapy applications such as dermatological and intra-operative procedures, where a short range treatment is needed, we have studied the use of nuclear reactions induced by low energy ions from small accelerators. A very suitable reaction is D(3He,p)4He, using 3He+ ions with energies of about 800 keV. The resulting protons have energies above 17 MeV and could deliver significant radiation dose depending on the accelerator 3He+ beam current and the irradiation time. The deuterium containing target was prepared by reactive magnetron sputtering of titanium in Ar and Ar+D2 radiofrequency plasma on a substrate of Silicon. The Ti-D stoichiometry and deuterium content was determined by Ion Beam Analysis. The accelerated 3He+ beam was provided by the 2.5MV Van de Graaff accelerator at the National Laboratories of Legnaro, INFN, Italy. Proton yield as a function of the beam current at different forward scattering angles has been studied for the energies of the incoming 3He+ in the 700keV – 800keV energy interval. The irradiated volume and the radiation dose in biological tissues as a function of the proton energy and proton yield has been estimated. Possible applications in small animal treatment studies as well as potential clinical radiotherapy applications are discussed.

1. Introduction

Therapies based on the use of accelerated hadrons (hadron therapy) nowadays are a very important aspect of medical radiation therapy of cancer. Hadrons possess a very useful property: the strong increase of the linear energy transfer (LET) at the end of the charged particle trajectory in matter, the so-called Bragg Peak. Such a high energy release allows an in-depth “conformal” treatment of tumor tissues [1, 2]. The main radiobiological advantage of such a conformal therapy is the release of the
highest possible dose to the tumor, while protecting the surrounding normal tissues as much as possible.

Using modern imaging technologies such as Computed Tomography (CT), Single Photon Emission Computed Tomography (SPECT), Positron Emission Tomography (PET), Magnetic Resonance Imaging (MRI), etc., it is possible to obtain a three-dimensional image of the tumor. Then the tumor irradiation can be conducted from diverse angles thus decreasing drastically the dose released in the surrounding tissues. This is the principle of three-dimensional conformal radiotherapy (3DCRT) [2,3]. One way to realize 3DCRT is to use a broad hadron beam passing through collimators designed to match the tumor contour shape at each angle of irradiation. The in-depth dose distribution is shaped by specific milled compensators to reduce the range of hadrons [4, 5]. Another way to deliver the dose in the tumor is to decrease the hadron beam size to a narrow mono-energetic “pencil” beam and to make it scan across the object to achieve the planned dose. The scanning is conducted in x,y plane perpendicular to the beam direction and the depth scan (in z direction) is realized applying appropriate energy of the hadrons’ beam [5].

Proton beams, being the lightest hadron particle, features several advantages as for the radiation therapy. However, its mass is high enough to have a relatively low lateral side scatter in the tissue. As a consequence, the proton beam has a low divergence, maintains the preliminary shape and delivers the planned dose at the tumor. In addition the calculation of the stopping power in the tissues is simple; the computer simulations are working quite well and finally there is no significant tail after the Bragg Peak. This is important when vital or radiation fragile organs, such as the genital system, eyes, brain, the spinal column, etc., are situated behind the tumor tissue.

Typical energies to conduct effectively radiation therapy of tumors situated in-depth of human body are in the range 50 to 250MeV for protons and about 120–400MeV/nucleon for ions like carbon [6]. These energies can be supplied by charged particles accelerators such as linear accelerators (linacs), cyclotrons or synchrotrons. The choice of the accelerator depends on the particular requirements (type of hadrons, beam currents, etc.) but in general cyclotrons and synchrotrons are the accelerators mostly used for hadron radiotherapy. The equipment for the hadron therapy includes the accelerator, the beam guidance system, the gantry (in the case of patient irradiation from many directions), and it requires a lot of space, especially in case of high energies or heavy ions. However, application-oriented proton accelerators, such as the ones for industrial and medical purposes, are simple and less expensive. The development of the modern technologies and the application of superconducting materials allow substantially reducing the size of the cyclotron, which can easily mounted in the gantry. This also removes the need of a separate cyclotron control room and a proton transport beam line.

In this article we present the results from an experimental study about the use of the high Q-value (Q = 18.35MeV) exothermic nuclear reaction D(3He,p)4He for possible proton radiotherapy applications. Protons with energies up to 17.4MeV are obtained using relatively low-energy helium beams (about 800keV), supplied by a small-size accelerator, adequate for hospital usage. The idea to exploit the reaction D(3He,p)4He for proton therapy has been first proposed in [7] and a thorough analysis of possible applications has been conducted. The aim of the experiment described in the present paper is to measure experimentally the proton yield from the reaction for a particularly designed deuterium-containing target and to draw conclusions about possible radiotherapy applications.

2. Materials and methods

2.1. Target preparation

The deuterium containing target was prepared by reactive magnetron sputtering of Titanium in Ar and Ar+20%D2 radio-frequency plasma at the total pressure of 3.5 10^{-3} mBar, on a substrate of Silicon
(nominal thickness 85µm, Boron doped). The deposition was performed in two steps. First a thin layer of Titanium for adhesion purposes was deposited using pure (N60) Ar plasma. Then a second layer of Ti-Dₓ compound was formed using Ar+20%D₂ gas mixture.

2.2. Target characterization
To determine the target layer structure we performed a Rutherford Back-Scattering (RBS) analysis using a proton beam with energy of 2MeV (at the AN2000 accelerator of the National Laboratories of Legnaro, INFN, Italy). The target was placed with the “deuterated” layer facing the beam. The backward scattered protons were detected at 155° from beam direction using an ion-implanted-silicon charged-particle detector with minimum depletion depth of 100µm (detector A of figure 1). The whole chamber acted as a Faraday cup to measure the accumulated beam charge. A spectrum of the backscattered protons from the target at an angle θ = 155° is shown in figure 3.

The amount of Deuterium was determined from the back-scattering spectrum (figure 3), which offers the ratio between the quantities of Titanium (Nₜ) and Deuterium (Nₓ): Nₓ/Nₜ = 1.28. We also measured the Deuterium areal density, ρₓ = 1.7 x 10¹⁸ at/cm² [8]. The measured thickness of TiDₓ was about 250nm.

3. Proton yield measurements
To study the reaction D(³He,p)⁴He we have used a ³He beam delivered by the same AN2000 accelerator. As it has been shown in [9-11] the cross-section for this reaction has highest values for energies in the range 700keV – 800keV that we have picked up for our measurements. The Proton yield at different forward scattering angles has been studied.
The experimental setup including two detectors is shown in figure 2. A partially depleted Si detector (minimum depletion thickness 100µm) 100µm Si detector was placed at 160° from the beam direction for measurements in the backward direction and for the assessment of the beam charge for spectra normalization. Another Si detector (Detector B in figure 2; totally depleted 1018µm thick) was used to detect the particles in the forward direction. The detector angular position φ was varied from -70° to +70° with respect to the beam direction. A passive Silicon layer with a thickness of 1008µm was mounted in front of the Detector B in order to stop all the protons in the detector depleted volume.

A spectrum of the particles (elastically scattered He-3 and reaction products) in the backward direction is shown in figure 4. The low energy part reveals the target layer structure and was also used for spectrum normalization, while protons and 4He particles originated from the D(3He,p)4He and D(3He, 4He)p reactions appear at higher energy values.

Proton spectra of the D(3He,p)4He reaction have been collected at different forward angles in the range −70° to +70° using 3He+ beams at 700 keV and 800 keV. Spectra of the detected particles in the forward direction, including the relative particle yield at different angles for both energies, are shown
in figure 5(a) and 5(b). Proton yield as a function of the angle of detection in the forward direction is shown in figure 6(a) (for E(\(^3\)He) = 700keV) and in figure 6(b) (for E(\(^3\)He) = 800keV).

![Figure 6(a)](image)

**Figure 6(a).** Measured proton yield from the reaction D(\(^3\)He,p)\(^4\)He at beam energies E(\(^3\)He) = 700keV and E(\(^3\)He) = 800keV

![Figure 6(b)](image)

**Figure 6(b).** Calculated dose in Gy/\(\mu\)C for protons from the reaction D(\(^3\)He,p)\(^4\)He at beam energies E(\(^3\)He) = 700keV and E(\(^3\)He) = 800keV

4. Discussion and conclusion

From the kinematics of the reaction D(\(^3\)He,p)\(^4\)He it follows that maximum energy values of the protons in the forward directions, after passing through about 90\(\mu\)m thick Si substrate at angle of 0°, is about 17MeV (at beam energy E(\(^3\)He) = 800keV) and 16.6MeV (at E(\(^3\)He) = 700keV). The range of these protons for in biological tissues is less than 3.2mm. For example, the range of protons in muscles for the two energies is 3.1mm and 2.9mm respectively (SRIM [12]). This fact limits possible applications to short range treatments only. A very thin \(^3\)He beam, bombarding the target, would irradiate a hemispherical tissue volume of 0.125cm\(^3\), if it is situated very close to the target [7]. Our measurements show that the integral delivered dose for such volume equals to 1.75\times10\(^4\) Gy/\(\mu\)C (at 700keV \(^3\)He beam) and 1.705\times10\(^3\) Gy/\(\mu\)C (at 800keV \(^3\)He beam). It is clear that to achieve radiation doses of 0.5 – 2 Gy, often used in proton therapy, one needs to go up with the beam current and the time of irradiation: for example to a beam current around 1mA for tens of seconds. However, in this case the main problem is not only the beam current limitations but also the sputtering of the layer caused by \(^3\)He and the heat dissipated in the target, although the thermal conductivity of Ti hydride is of same order of that of pure Titanium [13] allowing for efficient cooling schemes.

When a broader and more uniform beam is needed, as it is desired in case of dermatological or intra-operative treatment, the distance from the deuterium target to the biological object has to be increased up to several centimeters and the size of the target can be enlarged. Following [7] such geometry is referred as “topical radiation field”. Obviously, in this case, the dose will decrease with the square of the distance leading to larger irradiation times. An advantage however, is the possibility to enlarge the beam diameter to decrease the target heating.

To increase the number of emitted protons one could also increase the thickness of the deuterium-containing layer. A change of layer thickness of a factor of two to four would proportionally decrease the irradiation time or the beam current. Such a change can be obtained by sequential deposition of
several Ti and TiD$_2$ layers for mechanical stability. A further increase of the proton yield may be obtained by improving the deposition method to reach the TiD$_2$ stoichiometry.

Though the range 2.5 – 3mm of 17MeV protons in tissue is generally short, there are a number of possible applications such as dermatologic applications (skin cancer treatment), intraoperative treatment, tumor therapy of the vocal cords, nasal tumors, etc. [7]. Another application of this method is for R&D irradiation of laboratory small animal (mice), which requires a substantially lower range of the protons. Precise measurements of the radiation dose and therapeutic effect of protons in animals are scant today. One can believe that less-intensive proton beams can be successfully applied for experimenting radio-biological effects in small animals.

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