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Present status of accelerator-based BNCT: Focus on developments in Argentina

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HIGHLIGHTS

- The current status of projects and associated facilities for AB-BNCT worldwide is shown.
- Only low (few MeV) energy accelerators are included.
- The recent progress of the Argentine AB-BNCT program is described.

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ABSTRACT

In this work we provide some information on the present status of accelerator-based BNCT (AB-BNCT) worldwide and subsequently concentrate on the recent accelerator technology developments in Argentina.

1. Introduction

Right now several accelerator-based facilities for BNCT are being designed, constructed and some already tested at various centers around the world. The aim is to inaugurate the era of hospital-based facilities, moving progressively away from reactor-based facilities which, according to the prevailing consensus, are more costly and difficult to operate, to license, and, more importantly, are not suitable for installation in hospitals. The guiding criteria for such facilities should be their safety, simplicity, and lowest possible cost to allow the widest possible dissemination of BNCT as a therapeutic option.

We shall restrict ourselves to facilities based on low energy accelerators (producing proton or deuteron energies of a few MeV), since higher energies are likely to cause difficulties in a hospital environment due to activation and the need for heavy shielding.

It is well known that the best candidates for neutron-producing nuclear reactions are on one hand the endoergic ^{7}Li(p,n)^{7}Be and ^{9}Be(p,n)^{9}B and on the other the exoergic ^{9}Be(d,n)^{10}B reaction, among others.

^{7}Li(p,n) is best from a neutronic point of view, meaning that the neutron yield is highest and the spectrum quite soft, depending on the bombarding energy, but below 1 MeV for proton energies below 2.5 MeV. Of particular interest is the use of this reaction near-threshold (namely slightly above 1.88 MeV), where, in spite of the small yield the very low energy neutrons can be very efficiently utilized with very little moderation. On the down side li has very poor material properties and in addition produces a radioactive end product (^{7}Be), an undesirable feature for a hospital environment. Nonetheless there are projects based on this option:

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in the UK, Israel, Russia and Japan, some of them based on liquid Li targets to avoid the solid target to melt or deteriorate under the heat load delivered and the radiation damage induced by the powerful beams. These problems can be solved but represent additional issues to care about.

Other initiatives are focusing on ^{9}Be(p,n)^{9}B. ^{9}Be is a much better material and has no residual radioactivity but its yield, at energies suitable for ^{7}Li(p,n)^{7}Be, is quite small, so that higher-energy machines are required. About 4 MeV is probably the lower limit for this reaction to be used for AB-BNCT. Projects based on this option are moving forward both in Italy and Japan.

Turning to the exoergic reactions, ^{9}Be(d,n)^{10}B appears as a very promising candidate, particularly in connection with a thin target which helps to suppress a good part of the harder neutron spectrum. It has the advantages of the Be target, a stable end product (^{10}B) and already at very low bombarding energies (about 1.45 MeV) has a significant yield. This is the option being explored by our group in Argentina, as a first step in the development of accelerator technology, since it requires the smallest possible accelerator. We shall briefly describe the recent progress and the results obtained to date.

2. Materials and methods

2.1. Active projects around the world

Projects based on the ^{7}Li(p,n)^{7}Be are located, as mentioned, in the UK (Green et al., 2014), Israel (Halfon et al., 2014), Russia (Taskaev, 2014) and Japan. The UK and Russian machines are electrostatic (a dynamitron and a vacuum insulated tandem respectively) and are operating on still too low intensity beams for a therapeutic facility (around 1 to 2 mA on solid Li targets) and would need an upgrade in this respect. There are also two projects starting in Japan (Osaka and Nagoya) based on the dynamitron (Horiike et al., 2014; Tsuchida et al., 2014). The machine in Israel is an RFQ-DTL (Radio Frequency Quadrupole-Drift Tube LINAC) already operating on a liquid Li target with still modest currents of about 1.3 mA. The liquid target has been already shown to perform satisfactorily. There is also another project under way in Japan (Fujii et al., 2014, at the National Cancer Center, Tokyo) based on a LINAC and a solid Li target. The liquid Li option has also been studied in Japan (Kobayashi et al., 2014).

The projects based on the ^{9}Be(p,n)^{9}B reaction are located in Italy and Japan. The Italian project is based on an RFQ, intended to work at about 5 MeV and 30 mA, to produce thermal neutrons to treat superficial tumors (Pisent et al., 2014). The most advanced Japanese project, a large interinstitutional project centered around Tsukuba University (Kumada et al., 2014), is based on an RFQ-DTL designed to work at 8 MeV and a maximum current of 10 mA (Kobayashi et al., 2014).

2.2. The ^{9}Be(d,n)^{10}B reaction

This reaction has been carefully studied over a number of years by several groups, including ours (Capoulat et al., 2013, 2014a). In spite of this the experimental information is still scarce and more data would be desirable in the $\approx$1.4 MeV regime. However, enough is known to allow an evaluation of this reaction for AB-BNCT. This reaction leads to a neutron production of $(0.9 \pm 0.1)\ 10^{13}$ neutrons/s for a 30 mA deuteron beam. An $\approx 8\ \mu$m thin target maximizes the production of low energy neutrons stemming from the population of some highly excited states in ^{10}B. This reaction populating these states is effectively endoergic with a threshold of about 1 MeV. The neutron production of the beam of less than 1 MeV (the remaining energy after traversing the thin target), leading to high energy neutrons, is eliminated. It is interesting to point out that the maximum neutron energy for the 1.45 MeV deuteron beam is about 5.7 MeV, somewhat smaller than the highest neutron energy (6.1 MeV) produced by the 8 MeV proton beam to be used in the Tsukuba project. Even more significant is that 69% of the neutrons from the ^{9}Be(d,n)^{10}B reaction have energies below 1 MeV, while all the neutrons coming from the ^{9}Be(p,n)^{9}B reaction have significantly higher energies (Byrd et al., 1983). Those associated with the population of the ground state of ^{9}B have energies in the interval 3.64–6.14 MeV, while those populating the 2.35 MeV excited state are in the 1.84–3.71 MeV range. Most of the neutron yield is associated with these two states.

The results of the simulations for this reaction are quite promising. Our Monte Carlo simulations have shown that viable brain tumor treatments are feasible by means of low-energy deuteron beams (approximately 1.4 MeV) and simple AlF_3-based beam shaping assemblies (Capoulat et al., 2014a; Herrera et al., 2013).

In our quest for a full fledged accelerator we are starting with a single ended electrostatic machine of about 1.5 MV terminal voltage.

2.3. The machine

During the last few years we have been devoted to the development of such an accelerator and most of its sub systems. The principles underlying this machine have been already described (Kreiner et al., 2007, 2014a, 2014b). We shall concentrate in some of the recently completed aspects.

The machine is an ESQ (Electrostatic Quadrupole) accelerator. The strong transverse electric quadrupole fields help to keep the beam close to the beam axis, counterbalancing the space charge effects and effectively sweeping ions created along the acceleration column and hence preventing the generation of discharges along the tubes.

3. Results

3.1. The machine

The machine is an ESQ (Electrostatic Quadrupole): a single ended accelerator, to reach 1.5 MV (and hence 1.5 MeV deuteron beams for the ^{9}Be(d,n)^{10}B reaction) in a first stage and a tandem in the final stage (and hence about 2.5 MeV proton beams for the ^{7}Li(p,n)^{7}Be reaction). At present we have completed a smaller size prototype which is already running and producing quite intense beams (see Fig. 1). A larger machine is under construction.

The tubes have been completely developed in house. They are 100 kV units made of borosilicate glass insulating rings and stainless steel electrodes. They house the ESQ's, which are carefully centered and aligned to define an optical axis. Fig. 2 shows one of these tubes being centered on a numerically controlled milling machine.

3.2. The achieved beam transport

Proton beams of up to 10 mA have been transmitted through the machine and into a suppressed Faraday cup. The observation and beam diagnostics have been performed through the fluorescence induced by the intense beam in the residual gas. Fig. 3 shows three images of the beam propagating through the machine and the corresponding consecutive observation points. The upper image corresponds to the upper chamber of the accelerator, right before entering into the Faraday cup. The normalized emittance of this 10 mA beam has been determined to be $(0.40 \pm 0.05)\ \pi$ mm mrad.

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Fig. 1. 200 kV single ended machine.

Fig. 2. ESQ's within 100 kV tube during the centering and alignment process.

3.3. *The neutron production target*

The target is described schematically in Fig. 4. It consists of the thin Be layer onto which the ≈ 1.45 MeV deuteron beam is impinging. After traversing this layer and losing about 400 keV, the beam enters into a layer of a material resistant to radiation and hydrogen damage where it stops. These two layers are attached among themselves and to a Cu (Oxygen free) backing which is refrigerated efficiently through microchannels (Suarez Anzorena et al., 2013; Capoulat et al., 2014b).

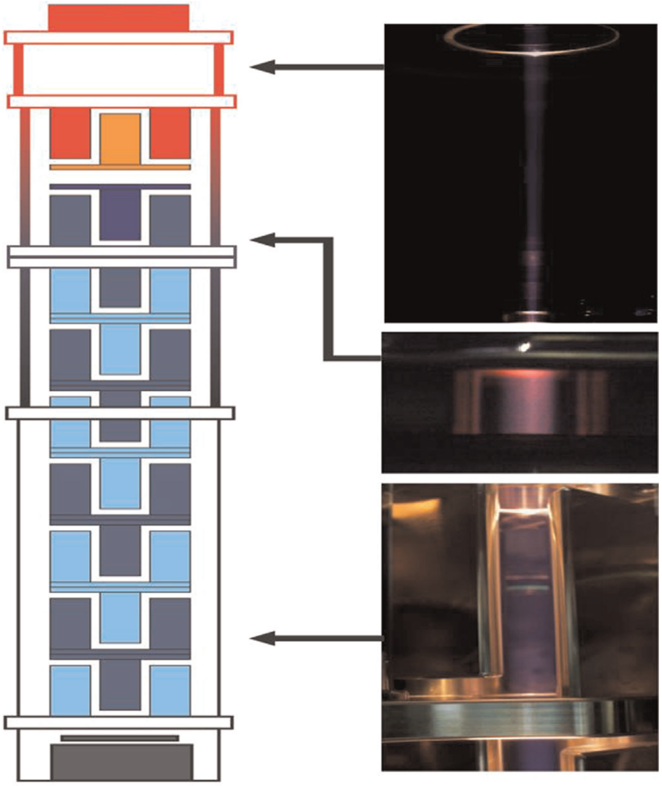

Fig. 3. Intense proton beam being observed through three different glass viewports and through the fluorescence induced in the residual H_2 gas. This figure shows three images of the beam propagating through the machine and the corresponding consecutive observation points. The lower picture (lower right hand side) is taken near to the entrance to the ESQ channel, the next picture up is taken at the entrance of the second tube and the upper image corresponds to the uppermost chamber of the accelerator, right before entering into the Faraday cup.

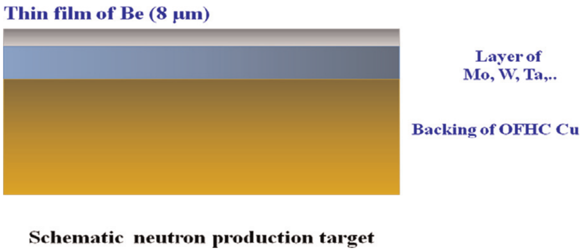

Fig. 4. Neutron production target. The beam is impinging from above on the ≈ 8 μm thin Be layer, followed by a radiation and hydrogen damage resistant layer and the refrigerating backing.

4. Conclusions

The different projects for AB-BNCT in progress worldwide are briefly reviewed. We restrict this review to facilities based on low energy accelerators (producing proton or deuteron energies of a few MeV), associated with the neutron-producing endoergic ^{7}Li(p,n)^{7}Be and ^{9}Be(p,n)^{9}B and the exoergic ^{9}Be(d,n)^{10}B reaction.

We concentrate on the ^{9}Be(d,n)^{10}B reaction since it requires the smallest-energy accelerator. This is the option being explored in Argentina, as a first step in the development of appropriate accelerator technology. A smaller scale single ended ESQ accelerator has been already built and tested, transmitting proton beams of up to 10 mA.

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