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Measurement of neutron spectra generated by a 62 AMeV carbon-ion beam on a PMMA phantom using extended range Bonner sphere spectrometers

R. Bedogni [a,*], K. Amgarou [b], C. Domingo [b], S. Russo [c], G.A.P. Cirrone [c], M. Pelliccioni [a], A. Esposito [a], A. Pola [d], M.V. Introini [d], A. Gentile [a]

[a] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati, Italy
[b] Grup de Recerca en Radiacions Ionitzants, Departament de Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
[c] Istituto Nazionale di Fisica Nucleare—Laboratori Nazionali dei Sud, Via S. Sofia 62, 95125 Catania, Italy
[d] Politecnico di Milano, CESNEF, Dipartimento di Energia, via Ponzio 34/3, 20133 Milano, Italy

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ABSTRACT

Neutrons constitute an important component of the radiation environment in hadron therapy accelerators. Their energy distribution may span from thermal up to hundred of MeV. The characterization of these fields in terms of dosimetric or spectrometric quantities is crucial for either the patient protection or the facility design aspects. To date, the Extended Range Bonner Sphere Spectrometer (ERBSS) is the only instrument able to simultaneously determine all spectral components in such workplaces. With the aim of providing useful data to the scientific community involved in neutron measurements at hadron therapy facilities, a measurement campaign was carried out at the Centro di AdroTerapia e Applicazioni Nucleari Avanzate (CATANA) of INFN-LNS (Laboratori Nazionali del Sud), where a 62 AMeV carbon ion is available. The beam was directed towards a PMMA phantom, simulating the patient, and two neutron measurement points were established at 0° and 90° with respect to the beam-line. The ERBSSs of UAB (Universidad Autónoma de Barcelona-Grup de Física de les Radiacions) and INFN (Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Frascati) were used to measure the resulting neutron fields. The two ERBSSs use different detectors and sphere diameters, and have been independently calibrated. The FRUIT code was used to unfold the results.

1. Introduction

The carbon-ion therapy constitutes a significant fraction of the hadron therapy. According to the statistics of PTCOG (Particle Therapy Co-Operative Group, ptcog.web.psi.ch), it currently represents about 10% of the treatments performed in the about 30 existing hadron therapy facilities worldwide, and the variety of malignancies treatable with this technique is increasing [1].

The energy of interest for cancer therapy ranges from several tens up to 400 AMeV for carbon ions. Because the kinetic energy is significantly higher than the binding energy per nucleon (<8 MeV), the interaction of these ions with matter includes inelastic reactions with target and projectile fragmentation. A significant neutron production is always present. The neutron yield is roughly proportional to the energy per nucleon and weakly depends on the atomic number of the absorber. For carbon targets and 62 AMeV ions, the neutron yield is approximately 0.3 per incident ion [2].

Neutrons emitted at small angles mainly come from projectile-target peripheral collisions, where the incident ion may lose one or more nucleon. This has been modeled with the abrasion–ablation model [3]. The energy distribution has a maximum at approximately half the projectile initial energy per nucleon and extends up to about twice the projectile initial energy per nucleon.

At large angles, the neutron emission is mainly given by the evaporation processes occurring in the target and in the projectile. Therefore, the spectrum is softer and the fluence is lower than in the forward direction.

At therapeutic energies, neutrons constitute the main concern for either the occupational radiation protection and shielding, or the patient protection. Concerning the latter aspect, the neutron field produces a whole-body exposure of the patient, whilst the clinical beam selectively irradiates the treatment volume. As a consequence, the risk of long-term secondary cancer due to neutrons may be higher than that associated to the clinical beam and its scattered components [4,5].

Experimental works have been performed to quantify the neutron exposure in the vicinity of tissue equivalent phantoms irradiated with carbon-ion beams. Works using high-resolution

* Corresponding author. Tel.: +39 694032608; fax: +39 694032364.
E-mail address: roberto.bedogni@lnf.infn.it (R. Bedogni).

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spectrometry techniques, like time-of-flight [6], normally focus on the high-energy component ($E > 20$ MeV). Works based on broad energy instruments like rem-meters [7,8] are also available in literature, but they cannot provide spectrometric information. In addition, the ambient dose equivalent (H*(10)) response of rem-meters only partially matches the fluence-to-ambient dose equivalent conversion coefficient in limited energy ranges [9,10]. The mentioned works indicate that in-room neutron ambient dose equivalent largely depends on the beam delivery technique (active or passive scanning), on the projectile energy per nucleon, and on the materials composing collimators, energy degraders and other beam components. Reported H*(10) values span in the interval 0.05—few mSv per prescribed Gy at 1 m from the isocentre.

The aim of this work is to provide measured neutron spectra, covering all energies from thermal up to the maximum production energy, for the forward (0° with respect to the incident beam) and the sideward direction of a 62 AMeV carbon-ion beam impinging a PMMA target simulating the patient. In spite of its limited energy resolution, the Extended Range Bonner Sphere Spectrometers (ERBSS) [11] is the only spectrometer able to simultaneously determine all energy components from thermal up to the maximum expected energy (~100 MeV). Whilst a standard Bonner Sphere Spectrometer (BSS) [12] relies on polyethylene spheres and can generally measure up to 20 MeV neutrons, an ERBSS includes polyethylene spheres with high-Z (lead, copper, tungsten) inserts. At energy above 20 MeV, the inserts act as neutron multipliers and energy degraders through (n, xn) reactions. The response of the spectrometer is therefore extended in energy up to the GeV.

The experiment described in this work took place at the INFN-LNS (Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud, Catania, Italy). The ERBSSs operated by the UAB and INFN groups were used to determine the neutron fluence spectra and the dosimetric quantities, namely the ambient dose equivalent H*(10).

The FRUIT code [13,14] was used to unfold the experimental data.

The UAB and INFN ERBSSs use different detectors, different set of spheres and have been independently calibrated. Comparison exercises [15,16] demonstrated the compatibility and the equivalence of these spectrometers. Particularly, they have been compared in the neutron field produced by a 62 MeV proton beam on a PMMA target [17]. Both spectrometers were used to determine the neutron spectra in the forward and sideward directions, obtaining coherent results (less than 5% difference in terms of total neutron fluence).

2. The UAB and INFN spectrometers

In the configuration used for this work, the INFN-ERBSS consisted of 7 polyethylene spheres, whose diameters are here labeled in inches units for convenience (2 in., 3 in., 5 in., 7 in., 8 in., 10 in., 12 in.), plus three extended range spheres with the following composition:

7(Pb): external diameter 7 in.; it includes an internal 4 in. polyethylene sphere surrounded by 1.27 cm of lead;
7(Cu): external diameter 7 in.; it includes an internal 4 in. polyethylene sphere surrounded by 1.27 cm of copper;
12(Pb):external diameter 12 in.; it includes an internal 3.15 in. polyethylene sphere surrounded by 1 cm of lead.

The UAB ERBSS relies on 8 polyethylene spheres (2.5 in., 3 in., 4.2 in., 5 in., 6 in., 8 in., 10 in. and 12 in.). A 1 mm thick cadmium (Cd) cover may be used in conjunction with the three smallest spheres and the resulting configurations are called 2.5(Cd), 3(Cd) and 4.2(Cd). The following extended range spheres are also included:

7(Pb): external diameter 7 in.; includes an internal 4 in. polyethylene sphere surrounded by 2.54 cm of lead;
7(Cu): external diameter 7 in.; includes an internal 4 in. polyethylene sphere surrounded by 2.54 cm of copper.

Details on the central detector, the response matrix and the calibration of the two spectrometers may be found in Refs. [15–21] for INFN system and in Refs. [15–17,22,23] for UAB system. For the purposes of this work it is worth recalling that the overall uncertainty of both response matrices was estimated as ±3% in the energy range below 20 MeV. As an example, the response matrix of the UAB ERBSS is reported in Fig. 1.

Because the neutron fields to be measured in this experience are expected to include large high-energy components ($E > 20$ MeV), a special consideration about extended range spheres and their uncertainty was done as follows.

Whilst the low-energy ($E < 20$ MeV) response of an ERBSS can be easily verified in monochromatic fields, no "pure" high-energy calibration fields are available in practice. Consequently, there is no direct way to estimate the uncertainty of the simulated high-energy response of the spheres. On the other hand, computational works have been carried out to assess the code-to-code variability in determining the high-energy response of extended range spheres [24]. In addition, simulation codes have been compared with experimental data on neutron production from targets at different energies and angles [25,26]. As a general conclusion, the code-to-code differences are limited to ±10% when estimating the ambient dose equivalent, the neutron fluence or the fluence in broad energy intervals. Following this indication, a ±10% uncertainty was assumed in this work for the high-energy response of the ERBSS. Because only the extended range spheres practically respond to high-energy neutrons, this uncertainty was only applied to the extended range spheres. The uncertainty of the response of standard polyethylene spheres, mainly responding to low-energy neutrons, was kept to ±3% as obtained in the validation experiments with mono-energetic neutron beams below 20 MeV.

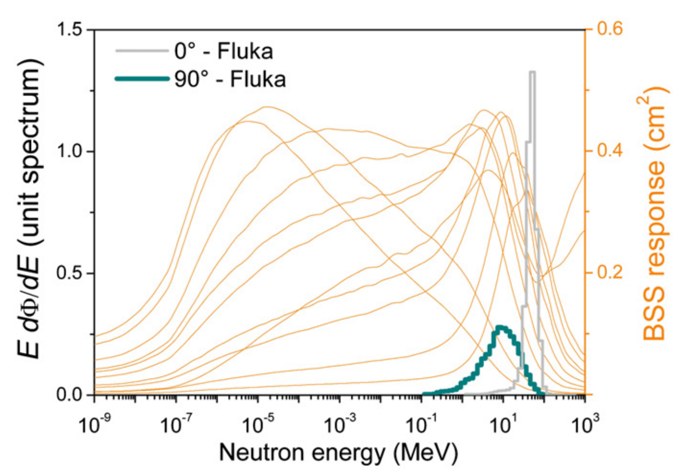

Fig. 1. Simulated neutron spectra in the forward (0°) and sideward (90°) directions superposed to the response functions of the UAB extended range Bonner Sphere spectrometer.