CHARACTERIZATION OF NEUTRON BEAMS FOR BNCT APPLICATIONS

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ABSTRACT

In this paper we present the current activity of the Nuclear Measurements Laboratory of DIMNP in the BNCT field. This activity is focused on the experimental characterization of BNCT neutron beams: in particular to verify the results obtained with Monte Carlo simulations used to design these facilities, and to calculate the neutron and gamma doses delivered to the patient during the BNCT treatment.

Introduction

The design of a BNCT facility relies on the obtainment of appropriate neutron beams and is normally performed using Monte Carlo codes, like MCNP [1]. To verify the beam has the characteristics requested from the BNCT protocols, and to estimate the neutron doses received by the patients during the BNCT treatment, it is necessary to characterize the neutron beams of this facility from an experimental point of view.

This characterization is based on the determination of energy distribution of the flux at the irradiation position. In Nuclear Measurements Laboratory (NML) of DIMNP, several types of neutron detectors are used: in the fast spectrum region the characterization of the beam is performed with Superheated Drop Detectors (SDDs) and activation threshold detectors, while activation detectors are also employed in the epithermal and thermal region.

In parallel to this activity, the in-vivo prompt gamma rays spectroscopy is studied. A preliminary apparatus to reveal this type of radiation has been setup.

Superheated Drop Detectors

Superheated drop detectors (SDDs), also known as bubble detectors, consist of uniform emulsions of over-expanded fluorocarbon and/or hydrocarbon droplets dispersed in an inert matrix such as a gel or a polymer tissue equivalents [2, 3]. They operate like a bubble chamber: the superheated droplets vaporize upon exposure to high-LET recoils produced by neutron interactions, thus generating macroscopic bubbles (fig.1).

Fig.1. Vials of superheated emulsion irradiated (on the left) and not irradiated.

The number of droplets formed can be detected in three ways. If the detector is of the active type, there is a piezoelectrical transducer that picks up the acoustic signal produced by the explosion of the bubbles when drops vaporize. These signals are amplified and fed to analogue circuitry for amplification, rectification and low-pass filtering, followed by analogue-to-digital conversion and sampling. The microprocessor evaluates shape and amplitude of the signals, and if these meet the acceptance criteria of a real bubble-formation event, a pulse is counted. With passive devices (integrating meters), the bubbles are optically counted or the volume variation after the formation of the bubbles in the gel is measured. In the second case the detectors are vials whose bottom part contains the superheated emulsion, while the top part contains an inert gel: when exposed to

neutrons the superheated drops vaporize and displace an equivalent volume of gel into the graduated pipette. The SDD detectors are not affected by the low-LET radiation (photons) and their sensibility varies with the degree of superheat (i.e. the operating temperature): the higher is the degree of superheat, the lower the minimum energy that the secondary charged particles, and therefore the primary neutrons, must impart to the droplets in order to nucleate their evaporation. This permits to achieve a response function suited for neutron spectrometry and dosimetry: by changing the temperature (normally with step of 5 °C from 25 °C to 55 °C) of the superheated drop detectors, is possible to generate a series of different neutron threshold responses, which permits the measurement and deconvolution of neutron spectra in the range 0.3-10 MeV.

In the NML the applicability of these nested threshold curves to neutron spectrometry was verified with radionuclide Am-Be neutron sources of well known spectrum and with measurement at two BNCT facilities, the reactor R2-0 of Studsvik (Sweden) and the reactor Tapiro of ENEA-Casaccia (Italy) [4]. The interpretation of the neutron source irradiation results, including uncertainty estimates, were performed by a "few channel" unfolding code and with Monte Carlo codes. Few-channel unfolding is the deconvolution of a spectrum over a number of energy bins higher than the number of experimental data (or the number of detectors, in this case). The final results is an estimate of the dose equivalent with an uncertainty in the order of 10-15%.

Threshold Detectors

The principle of this kind of detector is based on the use of thin disk probe with a threshold energy (generally of the order of several MeV) in the activation cross section: the probe is activated in a neutron filed and then its radioactivity is counted. Selecting materials with a different threshold energy, it is possible to obtain information about the fast energy spectrum of the neutron field from probe measurements. However, in the evaluation of the detector response, it is necessary to take in account the uncertainty about the exact value of the threshold.

After a preliminary phase of selection of the appropriate material for the probe, we focused our attention on the following reactions with gold and indium: $^{58}Ni(n,p)^{58}Co$ and $^{115}In(n,n')^{115m}In$.

The choice of the material detector was based on its availability, attitude to be transformed in a thin disk shape, value of its threshold and half life of the nuclide produced.

Some nickel and indium disks, covered by cadmium to eliminate the thermal activation, have been irradiated at the Tapiro reactor and the activation of the disks were measured with a HPGe detector. The gamma peaks at 811 keV for ^{58}Co and at 336 keV for ^{115m}In have been clearly detected and the activation of the probe was calculated. We will compare these values with the activations calculated simulating the irradiation setup with the MCNP code: this will represent a significative test for the results of MCNP code obtained in the design of the epithermal column of the Tapiro reactor for BNCT applications. In future we will test other types of materials to establish, if possible, an appropriate set of threshold detectors that could perform a spectrometry characterization of the entire fast energy range of the neutron spectrum.

Activation Detectors

This technique relies on the selective absorption of neutrons by suitable materials, which present high and isolated resonances in the epithermal energy region of the absorption cross section. A probe (thin foil) of this material is irradiated in a neutron field and then the induced activation is counted. Various materials can be used to this scope (In, Au, Mn, etc.) and two different techniques can be exploited:

- “normal sandwich”: irradiation of two identical foils, one of them covered by cadmium in order to eliminate the neutron below 0.4 eV (i.e. to eliminate the thermal components of the neutron flux)

- "triple sandwich": irradiation of a sandwich of 3 foils of the same material all inserted into a cadmium cover.

A standard formalism [5-7] exists to calculate the thermal neutron flux when the "normal sandwich" approach is used: the difference between the activation of the bare probe and the activation of the cadmium-shielded probe permits to calculate the thermal contribute to the activation and consequently the thermal neutron flux. If the flux is of the 1/E type it is also possible to calculate the epithermal flux.

In the "triple sandwich" case, it is possible to calculate the flux corresponding to the resonance energy of the irradiated material [5, 8], known the activation of the sandwich foils. Fig.2 is drawing the activation (calculated by MCNP) of a sandwich of three foils of indium (with a diameter of 20 mm and a thickness of 0.13 mm) inserted in a isotropic neutron field. The contribution of the neutron with the resonance energy (1.457 eV in the indium case) is very low for the internal foil because this neutrons are almost completely absorbed by the external foil. So it is possible to isolate the contribute of the neutron with resonance energy (and to calculate the flux in correspondence of it) by doing the difference between the activation of the external and the internal foils.

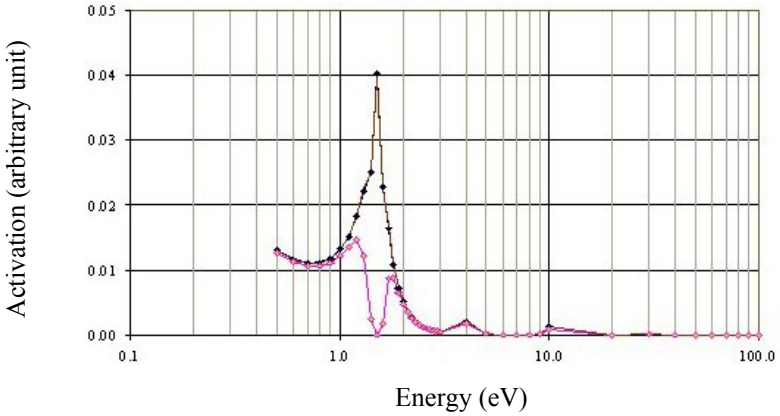

Fig.2. Activation with an isotropic neutron field for the foils of a "triple sandwich" [8] (fuchsia line: internal foil; other lines: external foils)

The error of this method is longer than in the case of "normal sandwich" because the formulae are based on the difference between two activations. A correct application of this technique (also known as sandwich method), which is theoretically described only for isotropic fluxes, would require the knowledge of the angular distribution of the flux.

For the normal sandwich approach we have use gold: the reactions of activation is $^{197}Au(n,\gamma)^{198}Au$. For triple sandwich we used both gold and indium, for the latter material the reaction is and $^{115}In(n,\gamma)^{116m}In$. Both this materials have an elevated and marked resonance in the lower part of the epithermal energy range (1.457 eV for indium and 4.905 eV for gold): these resonances contribute almost completely to the total activation (96% for indium and 95% for gold). Other materials show resonances at higher energy (^{55}Mn, ^{63}Cu and ^{59}Co), but this resonances are smaller than those of gold or indium and often these resonances are too close together that it is difficult to distinguish each contribute (therefore the error in the calculated value of the flux will be longer). The activation after the irradiation inside the reactor is measured with a NaI scintillator or with a HPGe detector.

The gold and indium triple sandwiches have been extensively used to verify the punctual intensity, in correspondence of the resonance energies, of the neutron flux inside the epithermal column which is being developed at the reactor Tapiro: this data will be compared with the values calculated by the MCNP simulation of the reactor. The system used (material and dimensions of the probes, irradiation procedures, etc.) was already successfully tested with the irradiation facilities available in the NML.

Prompt gamma ray detection

In determining the dose for BNCT, it is important to measure the prompt gamma ray produced by boron as well as the thermal neutron fluence. The Prompt Gamma ray Spectroscopy (PGS) is devoted to the determination of in-vivo boron concentration during the BNCT treatment, from which it is possible to calculate in-vivo the gamma dose delivered to the patient. Such information is obtained through the detection of the prompt gamma rays emitted in the $^{10}B(n,\alpha)^{7}Li$ and $^{1}H(n,\gamma)^{2}D$ reactions, respectively of 477 keV and 2.22 MeV.

A preliminary apparatus to detect the prompt gamma rays was setup. A vial of 100 cc containing a boric acid solution, simulating the tumor with a high concentration of boron, was inserted into a tank of pure water that simulates the human brain. The sample is inserted in a neutron field produced by an Am-Be radionuclide neutron source of 30 mCi and the prompt-gamma rays that the sample radiates were measured by a HPGe detector. The boron peak and the hydrogen peak have been individuated: the first has a trapezoid shape (fig.3) because of the Doppler shift caused by the Doppler shift due to the motion of ^{7}Li which emits the radiation [9].

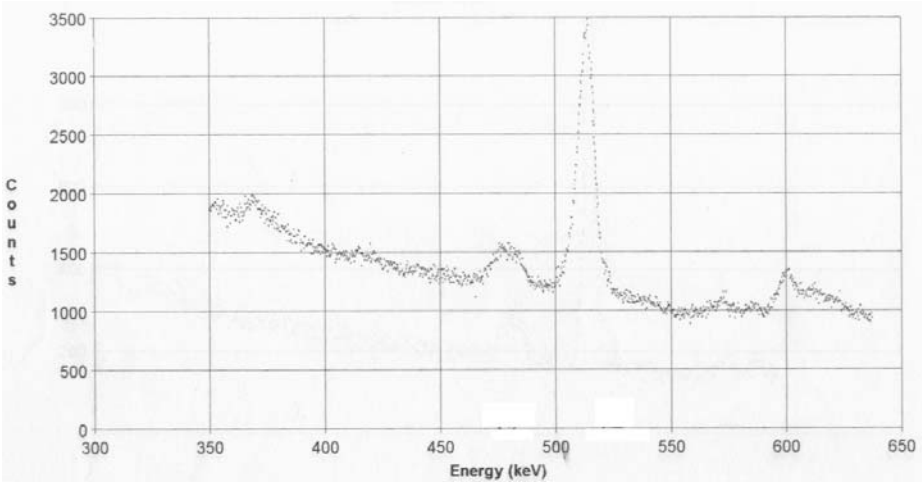

Fig.3. Spectral data plot of the prompt gamma ray emitted (the 511 keV peak is the annihilation peak).

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