NAA Using the Photoneutrons of a LINAC as a Neutron Source

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Abstract: Linear accelerators working above 8 MV produce photoneutrons that represent a radiological risk in the patient and hospital staff. In this work a moderator has been designed in the aim to use the photoneutron field to perform neutron activation analysis (NAA) of small samples. The moderator has been designed using Monte Carlo methods, here the photoneutron spectrum is modified by the moderator having the maximum thermal neutron flux in the moderator cavity where the sample to be analyzed is located.

Keywords: Neutron activation; Photoneutrons; LINAC

1. Introduction

When a medical linear accelerator (LINAC) operates above 8 MV, photonuclear reactions occur mainly of the type (γ, n), in the head of the accelerator [1].

Photoneutron spectrum produced in the LINAC has two components: Evaporation and the Knock off as it is shown in equation 1. [2].

$$\Phi_E(E) = A\,\frac{E}{T^2}\,\mathrm{Exp}\left[-\frac{E}{T}\right] + B\,\frac{\ln\left|\frac{E_{max}}{E+S}\right|}{\int_0^{E_{max}-S}\ln\left|\frac{E_{max}}{E+S}\right|dE} \qquad (1)$$

In this equation A and B are normalizing factors, T is the nucleus temperature, E_{max} is the maximum energy that neutrons have, this is mainly the LINAC voltage, E is the neutron energy and S is the neutron binding energy.

The Knock off neutrons are produced when a photon collides directly with a neutron in the nucleus. Here, the incoming photon delivers all its energy and the neutron is ejected from the nucleus.

In the mechanism of evaporation the photon transfers its energy to the nucleus, which is distributed among all nucleons, eventually the energy transferred to a neutron near the nucleus surface is enough to overcome the neutron binding energy and it is ejected [3, 4].

In a radiotherapy room the epithermal and thermal neutron fluence is constant regardless the distance from the isocenter. Figure 1 shows the behaviour of thermal neutrons in function of the distance [5]. In this figure is also included the source term described by equation 1.

Thermal and epithermal neutrons remain constant throughout the treatment room regardless the distance to the isocenter, ic; this is named room-return. On the other hand, fast neutron decreases as the distance to the isocenter increase.

For 15, 18 and 20 MV LINACs the neutron yield is approximately 10^{12} neutrons per treatment Gy [6] having a spectrum alike to spectra shown in figure 1.

In 2008 Polaczek *et al*. [7] determined the thermal neutron flux from the activation of Na^{23} from mammalian bone. using a 20 MVLINAC applying 90 Gy on the sample. They observed a thermal neutron fluence rate of $2.49\cdot10^5$ cm^{-2} s^{-1}

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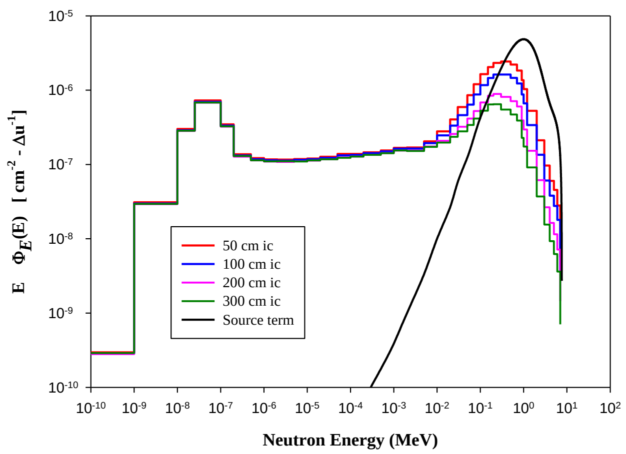

Figure 1. Neutron spectra inside a LINAC hall

Neutrons are secondary and undesirable radiation produced in LINACs; in the treatment room epithermal and thermal neutrons remain constant regardless the distance while, fast neutrons can be modified with a proper moderating media increasing the amount of thermal neutrons that could be used as neutron source for neutron activation analysis.

The objective of this work is to design a moderator to be used for neutron activation analysis using the LINAC´S photoneutrons as source term.

2. Materials and methods

2.1. Calculations

Using the MCNP5 code [8] neutron spectra were calculated in the center of a polyethylene cylinder, to select the appropriate size to perform the NAA [9-11], it was decided to use the cylinder whose dimenssions gives the maximum value of thermal-to-fast neutrons ratio, this ratio was used as figure-of-merit, FOM.

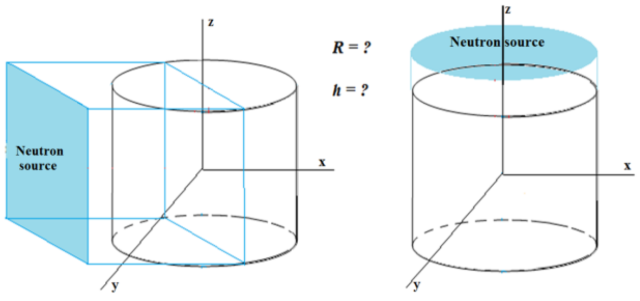

Figure 2. Models used during Monte Carlo calculations

Calculations were carried out using 2 irradiation geometries: one was with a square source located laterally, another was with a disk source located above the moderator, as shown in figure 2.

The source term for this calculations was obtained from literature [5]. In order to design the best cylindrical moderator dimenssions, for both sources, Monte Carlo calculations were carried out for polyethylene cylinders with the following sizes: 12.7 Ø x 12.7 cm^2, 15.24 Ø x 15.24 cm^2, 17.78 Ø x 17.78 cm^2, 20.32 Ø x 20.32 cm^2 , 22.86 Ø x 22.86 cm^2 and 25.40 Ø x 25.40 cm^2 looking for the best thermal-to-fast ratio.

2.2. Measurements

Induced activity was determined in 4 solutions of manganese sulfate de 0.5, 0.75 y 1 g, prepared in 10 ml graduated flasks, which were taken to polyethylene cylindrical containers with a capacity of 12 ml. Two were prepared at the same concentration in order to cover one of them with cadmium and observe potential interference due to reactions with fast and epithermal neutrons [12].

The photoneutrons produced by a LINAC were used to activate the samples; The linear accelerator used as neutron source is a Varian LINAC model CLINAC iX of 15 MV from the Cancer center of Tepic, Nayarit.

The samples were placed in the center of the moderator, that was located to 180 cm from the isocenter. Samples were irradiated for 4 minutes, along this time 12 Gy were applied to the isocenter at a rate of 5 cGy/s; the isocenter was 5 cm-deep of a solid water phantom.

Induced activity in the samples was measured with a gamma-ray spectrometer with 7.62 Ø × 7.62 cm^2 NaI(Tl) scintillator.

3. Results

3.1. Monte Carlo calculations

Neutron spectra at the centre of polyethylene cylinder due to the lateral source, in terms of moderator size, are shown in figure 3.

In figure 4 are shown the spectra due to cylinders irradiated with the upper source.

In figures 3 and 4 can be noticed that as the polyethylene radius increases the high energy neutrons decreases while the thermal neutron increases in comparison with high energy neutrons.

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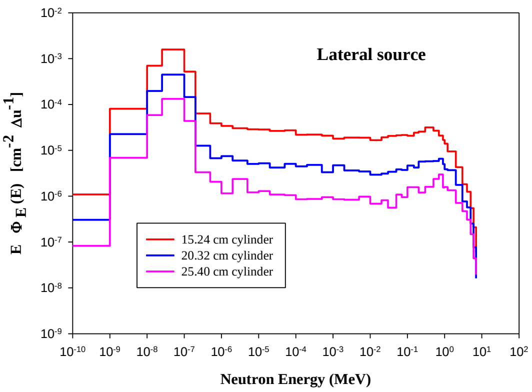

Figure 3. **Neutron spectra at the center of 15.24, 20.32 and 25.40 cm-diameter cylinders irradiated with the lateral source**

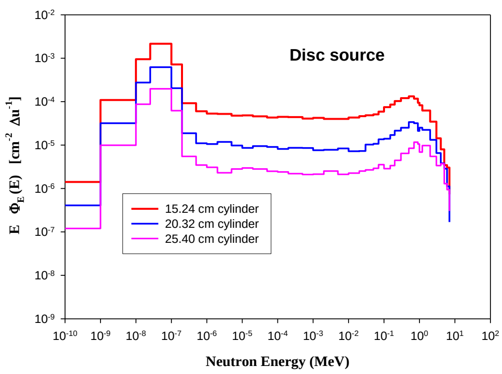

Figure 4. **Neutron spectra at the center of 15.24, 20.32 and 25.40 cm-diameter cylinders irradiated with the upper source**

Neutron spectra at the center of 20.32 Ø x 20.23 cm^2 cylindrical moderator when is irradiated with the lateral and upper source are shown in figure 5.

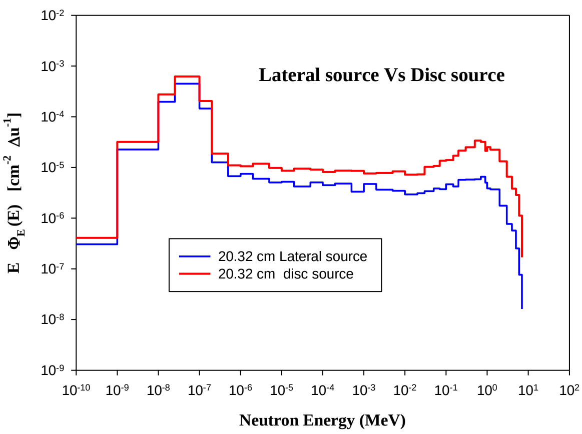

Figure 5. **Spectra at the centre of 20.32 cm-diameter moderator due to lateral and upper source.**

Here, with the lateral source a smaller amount of neutrons reach the centre of polyethylene moderator in comparsion when the disk source is used, this is in agreement with results reported in the literature [13, 14]. Also it can be noticed that the thermal-to-fast neutrons ratio varies with the type or geometry used in the irradiations.

In figure 6 are shown the lethargy spectrum from the source term and the neutron spectrum at the centre of 20.32 Ø × 20.32 cm^2 moderator.

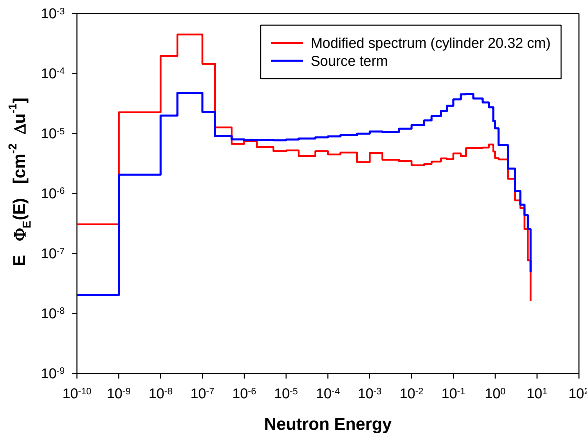

Figure 6. **Comparison between source term and spectrum at the 20.32 cm cylinder**

Here can be noticed that the high-energy peak of source term is reduced when neutrons reach the modera-tor center, on the other hand in the moderator´s center the amount of thermal neutron increases, this is because source term neutrons are moderated as they are trans-ported from the moderator surface to the center.

By looking the spectra behavior is difficult to decide the best moderator dimensions, where ideally we look for the largest amount of thermal neutrons and a smaller amount, or none, epithermal and fast neutrons that can be reached using a larger size moderator, however the amount of neu-trons in the LINAC is not too large, therefore the FOM was used.

In figure 7 are shown the thermal-to-fast neutrons ratios for 12.7 Ø x 12.7 cm^2, 15.24 Ø x 15.24 cm^2, 17.78 Ø x 17.78 cm^2, 20.32 Ø x 20.32 cm^2, 22.86 Ø x 22.86 cm^2 and 25.40 Ø x 25.40 cm^2, cylindrical moderators.

The best value for neutron activation analysis with thermal neutrons is located between the cylinder 20.32 Ø × 20.32 cm^2.

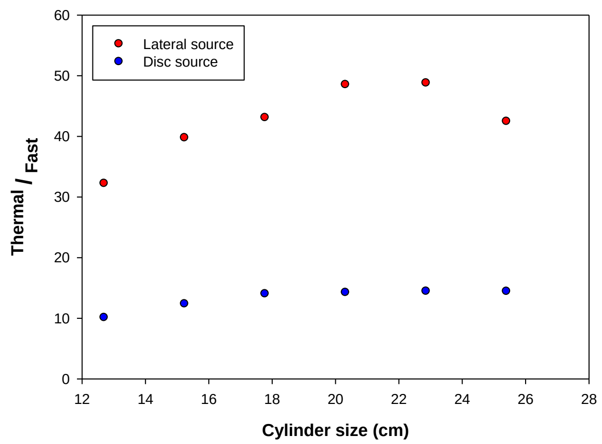

Figure 7. FOM for different size cylinders.

3.2. Experiments

In figure 8 are shown the pulse height spectra of Mn samples located at the centre of moderator with and without Cd filter.

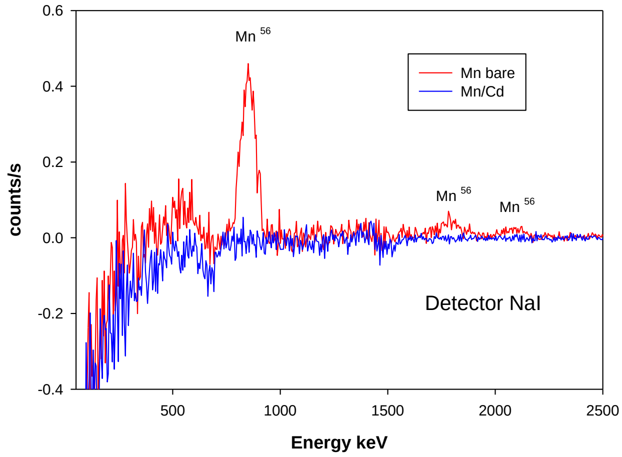

Figure 8. Pulse height spectra of induced activity in Mn with and without Cd filter

The Mn^{55} neutron capture reactions for thermal neutrons, epithermal and fast neutrons are,

$$Mn^{55}(n,\gamma)Mn^{56} \Rightarrow \gamma = 846\,keV \mapsto Thermal$$
$$Mn^{55}(n,\gamma)Mn^{56} \Rightarrow \gamma = 846\,keV \mapsto Epithermal$$
$$Mn^{55}(n,p)Cr^{55} \Rightarrow \gamma = 1528\,keV \mapsto Fast$$

Due to the capture cross section of cadmium, it is possible to filter the thermal neutrons so that we can determine possible interferences caused by the fast and epithermal neutrons. In figure 8 shows that activation of the manganese is due to thermal neutrons as not observed any peak in the spectrum for the sample wrapped with cadmium [12].

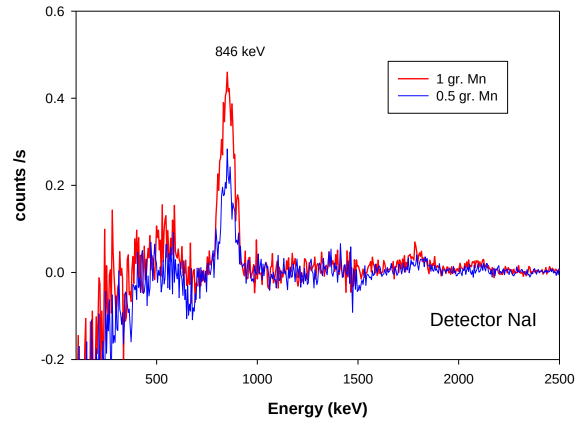

Figure 9. Pulse height spectra of induced activity in Mn solutions

The induced activity on solutions of Mn in term of the Mn mass in the solution is shown in the pulse height spectra in figure 9; here we can observe clearly that the level of activity decreases as the concentration decreases too.

The net count rates under the 846 keV peak were determined and related to the Mn mass, these values were fitted to a linear function of count rate and Mn mass. This is shown in figure 10.

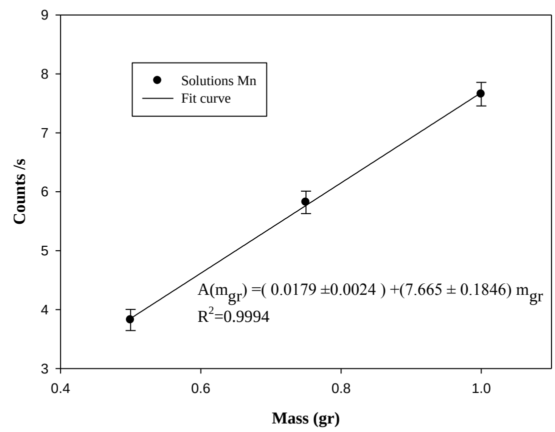

Figure 10. Net count rate under the Mn photopeak in terms of Mn mass

4. Conclusions

A neutron moderator has been designed allowing to induce activation in the treatment hall with a 15 MV linac. Samples of Mn solutions were located inside the modera-

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tor and were exposed to neutron field inside a 15 MV linac.

Count rates under the Mn photopeak are directly proportional to the amount of Mn mass in the samples.

Using the photoneutron field inside the treatment hall with a LINAC operating in Bresmsstrahlung mode above 8 MV are suitable to induce activation of isotopes with half-lives around few minutes.

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