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A BRIEF REVIEW OF NCT DOSIMETRY

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Abstract

Neutron Capture Therapy (NCT) offers a targeted approach for treating tumors, but its clinical implementation faces challenges in accurate dosimetry. This review focuses on the complexities of measuring the four key absorbed dose components — Photon, Hydrogen, Nitrogen, and Boron doses — in NCT treatments. Emphasis is placed on the importance of measuring the Boron dose, owing to boron-10's high interaction rate with thermal neutrons. While various methods, including gamma spectroscopy, are explored, they present logistical and safety challenges. The High-Pressure Xenon Gamma-ray Spectrometer emerges as a hopeful tool due to its high energy resolution and resilience against neutron flux. This study underscores the need for further research to standardize NCT dosimetry.

Keywords: *Neutron Capture Therapy (NCT); Dosimetry; Boron Dose Measurement; Gamma Spectroscopy; High-Pressure Xenon Gamma-ray Spectrometer; Thermal Neutrons*

Introduction

Shortly after the discovery of neutrons, Chadwick proposed Neutron Capture Therapy (NCT) in 1932. Goldhaber, in 1934, emphasized the significance of the naturally occurring boron-10 isotope's exceptional thermal neutron capture cross-section. NCT exploits the formation of secondary radiation when thermal and epithermal neutrons are absorbed by certain elemental nuclei. When tumor cells selectively accumulate elements like boron-10, lithium-6, cadmium-110, and gadolinium-157 and are subsequently irradiated with neutrons, the resulting radiation can damage these tumor cells with minimal impact on adjacent tissues (Beckman, I.N.).

Neutrons interact minimally with regular tissue; their primary interactions are nuclear captures with stable nuclei like ^{1}H, ^{14}N, and ^{10}B. Although living tissues are rich in ^{1}H (0.33 barns) and ^{14}N (1.7 barns), their capture cross-sections are so small that lethal

radiation damage is infrequent. Conversely, while ^{10}B (3990 barns) is scarcely found in living tissues, its neutron interaction rate is exceptionally high.

Upon neutron absorption, ^{10}B transforms into the excited nucleus of ^{11}B, which rapidly decays (10^{-12} seconds) into an α-particle and the ^{7}Li nucleus. In 6% of cases, their total energy is 2.8 MeV, and in 94% it's 2.3 MeV, since 0.48 MeV is carried away by a γ-quantum. These highly energized particles lose energy swiftly, and since a typical cell size is about 10μm, a significant portion of the energy is deposited directly into the cell housing the captured neutron (Taskaev, S.Y., Kanygin, V.V., 2016).

For NCT's clinical implementation, three key challenges must be addressed: sourcing neutrons suitable for clinical settings, selectively delivering boron to tumor cells, and ensuring accurate dosimetry throughout treatment. This review delves into the last challenge, focusing on NCT dose determination.

NCT absorbed dose measurement

Thermal neutral beams used in NCT yields four principal absorbed dose components in the treated tissue:

1. Photon dose (D_γ)
2. Hydrogen dose (D_h)
3. Nitrogen dose (D_N)
4. Boron dose (D_B)

Several methods have been introduced to measure these doses, including:

1. Ion chamber measurements;
2. Micro dosimetry measurements;
3. Gel dosimetry evaluations.

Despite the presence of multiple measurement methods, there is still no universally accepted standard for NCT dosimetry. Importantly, the first three radiation types — photon, hydrogen, and nitrogen — have a relatively minor impact on living tissue. As a result, the central emphasis in NCT dosimetry is on measuring the boron dose.

Among the available methods, gamma spectroscopy stands out as the only technique capable of directly measuring the absorbed boron dose. This method relies on the detection of a 478 keV gamma-ray, emitted during the rapid decay of a boron nucleus after capturing a neutron. However, implementing gamma spectroscopy in NCT presents several challenges:

1. The equipment for registering gamma quanta must be positioned near the patient during neutron irradiation, posing logistical and safety concerns.

2. The proximity of the neutron beam formation system — which consists of a moderator, a reflector, and an absorber — to the patient restricts the available space for placing the gamma spectroscopy equipment.

3. The detectors pick up not only the desired signals from boron decay but also spurious signals from other gamma quanta and neutrons, complicating the data analysis.

Given these constraints, the practical application of gamma spectroscopy in NCT dosimetry seems limited, underscoring the need for continued research to establish more feasible and accurate dosimetry methods.

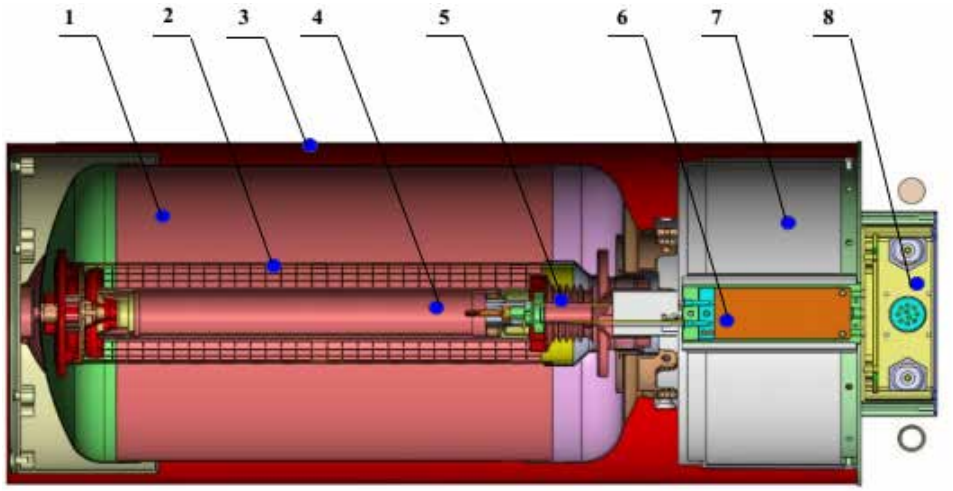
Materials and Methods

1. Considering these constraints, utilizing a gamma spectrometer with high energy resolution becomes paramount. The "High Pressure Xenon Gamma-ray Spectrometers" developed by the National Research Nuclear University MEPHI meets these criteria. The spectrometer boasts a 2% energy resolution for a 662 keV γ-ray, notably superior to NaI or CsI-based scintillation gamma detectors. This xenon-based spectrometer can measure γ-rays in an energy spectrum from 0.05 to 3 MeV (Alexander, S., Novikov, Sergey, E., Ulin, Valery, Dmitrenko, V., Chernysheva, Irina V., Grachev, Victor M., Krivova, Kira V., Shustov, Alexander E., Uteshev, Ziyaetdin M., Vlasik, Konstantin F. (2019); Gary, C., Tepper, Robert L., Palmer, Jon R. Losee, (1999); Ulin, S.E., Dmitrenko, V.V., Grachev, V.M. et al., (1995); Ulin, S., Novikov, A.V., Dmitrenko, K., Vlasik, K., Krivova, D., Petrenko, Z., Uteshev, A., Shustov and Petkovich, E. (2016); P'ya, S.N., Vlasik, K.F., Grachev, V.M., Dmitrenko, V.V., Novikov, A.S., Petrenko, D.V., Shustov, A.E., Uteshev, Z.M., Ulin, S.E. and Chernysheva, I.V. (2014).

The Xenon Gamma Spectrometer (XGS) is designed as a cylindrical pulsed ionization chamber equipped with a screen grid. This chamber is filled with a compressed gas mixture of xenon (Xe) and hydrogen (H_2), pressurized to approximately 40 atm. The inclu-

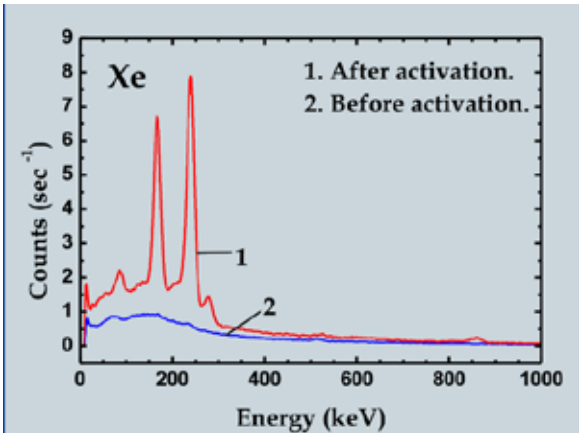
sion of hydrogen aims to enhance the electron drift velocity. Essentially, the XGS operates as a pulsed ionization chamber filled with high-purity, high-pressure xenon. Notably, the spectrometer is stable under radiation exposure and retains its functional properties even when subjected to a stream of neutrons. A schematic illustrating a cylindrical modification of this device, which incorporates a Frisch grid, is presented in Figure 1.

Figure 1. *The principal schematic of the xenon gamma-ray spectrometer:1 — Cylindrical pulse ionization chamber; 2 — Frisch grid; 3 — hermetic casing; 4 — anode; 5 — ceramic feed-through; 6, 8 –custom charge-sensitive amplifier; 7 — custom high-voltage supply*

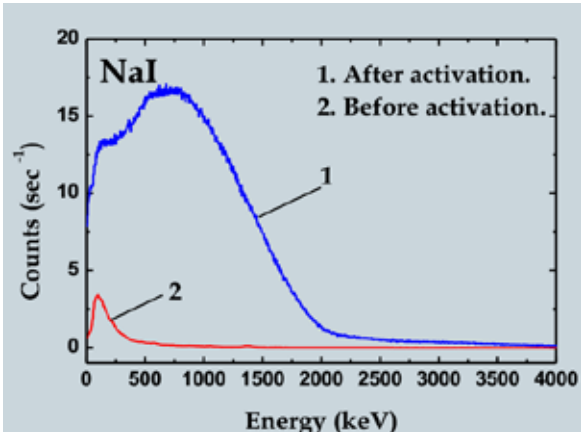


The High-Pressure Xenon Gamma-ray Spectrometer presents a distinct advantage over traditional scintillation gamma-ray spectrometers due to its resilience against neutron flux.

Spectra from High Pressure Xenon Detector (ø120 mm, L=500 mm, M= 1.8kg) before and after activation by Pu-Be neutron source (T=66 hours, fluence= 1.5*10 ^{10} neutrons)



Spectra from NaI detector (ø 80 mm, L = 50 mm, M = 0.9 kg) before and after activation by Pu-Be neutron source (T = 66 hours, fluence = 1.5*10 ^{10} neutrons)



Conclusion

The xenon gamma spectrometer has great energy resolution, can be made to any size, and is resistant to neutron flux. This characteristics make it viable for in-situ measurements during NCT sessions.

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