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Analysis of the relationship between neutron dose and Cerenkov photons under neutron irradiation through Monte Carlo method

Diyun Shu [a], Xiaobin Tang [a, b, *], Fada Guan [c], Changran Geng [a], Haiyan Yu [a], Chunhui Gong [a], Xiaodong Zhang [c], Da Chen [a, b]

[a] *Nanjing University of Aeronautics and Astronautics, Department of Nuclear Science and Engineering, 29 Yudao St., Nanjing, 210016, China*
[b] *Collaborative Innovation Center of Radiation Medicine of Jiangsu Higher Education Institutions, 29 Yudao St., Nanjing, 210016, China*
[c] *The University of Texas MD Anderson Cancer Center, Department of Radiation Physics, 1515 Holcombe Blvd., Houston, 77030, USA*

HIGHLIGHTS

- Relationship between Cerenkov photons and neutron dose in water was investigated.
- Neutron dose has good correlation with Cerenkov photons between 0.01 eV and 100 eV.
- Ratio of neutron dose to Cerenkov photons is energy-independent at specified case.
- Cerenkov radiation also has the potential application in neutron dose measurement.

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ABSTRACT

To theoretically explore the feasibility of neutron dose characterized by Cerenkov photons, the relationship between Cerenkov photons and neutron dose in a water phantom was quantified using the Monte Carlo toolkit Geant4. Results showed that the ratio of the neutron dose deposited by secondary electrons above Cerenkov threshold energy to the total neutron dose is approximately a constant for monoenergetic neutrons from 0.01 eV to 100 eV. With the initial neutron beam energy from 0.01 eV to 100 eV, the number of Cerenkov photons has a good correlation with the total neutron dose along the central axis of the water phantom. The changes of neutron energy spectrum and mechanism analysis also explored at different depths. And the ratio of total neutron dose to the intensity of Cerenkov photons is independent of neutron energy for neutrons from 0.01 eV to 100 eV. These findings indicate that Cerenkov radiation also has potential in the application of neutron dose measurement in some specific fields.

1. Introduction

Cerenkov radiation is a kind of electromagnetic radiation emitted when a charged particle travels at a speed greater than the phase velocity of light in the medium. Since its discovery, Cerenkov radiation has been widely used in different applications, such as nuclear physics and astrophysics (Jelley, 1955; Gorham et al., 2000; Pedaletti et al., 2013). The existence and velocity of high-speed particles can be identified by Cerenkov detector (Shiozawa et al., 1998; Haxton, 1987). Cerenkov radiation has also been extended to the application in biological imaging studies. As a new optical imaging modality, Cerenkov luminescence imaging has been researched for the potential of the diagnosis of cancer, the assessment of treatment efficacy, and the guidance of cancer surgery, etc (Ma et al., 2014; Tang et al., 2015; Robertson et al., 2009).

More recently, Cerenkov radiation has been applied in the dose measurement from therapeutic electron and photon beam irradiations, and the feasibility of its usage has been demonstrated through theoretical analysis and experimental verification (Glaser et al., 2013; Helo et al., 2014; Shu et al., 2016; Jang et al., 2012; Yoo et al., 2013; Jarvis et al., 2014). The clinical translation process of this technique is still under investigating.

In fact, Cerenkov photons can also be generated under neutron

* Corresponding author. Nanjing University of Aeronautics and Astronautics, Department of Nuclear Science and Engineering, 29 Yudao St., Nanjing, 210016, China.
E-mail address: tangxiaobin@nuaa.edu.cn (X. Tang).

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irradiation during the transportation of the secondary charged particles. Researchers have developed the water Cerenkov neutron detector for monitoring and tracking spent fuel storage, radioactive waste containers and special nuclear materials, etc (Dazeley et al., 2009, 2012; Cheon and Kim, 2015). The application of Cerenkov neutron detector has the advantages of both affordable and deployable in these areas. One of the recent developments is the determination of the thermal neutron flux in the facilities of thermal neutron source using the Cerenkov fiber-optic radiation sensor (Jang et al., 2013).

It is also very meaningful to obtain the neutron dose. The quality assurance and control of neutron beam requires the obtainment of the distribution of neutron dose, which is the critical process to ensure the therapeutic effect in boron neutron capture therapy. Besides, neutron dose measurement may contribute to radiation safety and protection of radiation workers or the public. In this study, we will explore the physics of Cerenkov radiation emission from neutron beams in water phantom, and theoretically investigate the relationship between Cerenkov radiation and neutron dose for the realization of neutron dose measurement using Cerenkov radiation, which has been seldom investigated.

2. Materials and methods

2.1. Physics principle of Cerenkov radiation from neutron interactions

The Cerenkov radiation from neutron irradiation is not directly generated from neutrons, but from the secondary charged particles. When the energy of a secondary charged particle is higher than Cerenkov threshold energy in the specified medium, optical photons will be emitted. The Cerenkov threshold energy can be calculated according to the refraction index of the medium.

$$T_{\text{threshold}} = E_0 \left(\frac{1}{\sqrt{1 - \frac{1}{n^2}}} - 1 \right) \quad (1)$$

Where $T_{\text{threshold}}$ is the threshold energy above which the charged particle can emit Cerenkov photons, E_0 is the rest energy of the charged particle, n is the index of refraction of the medium (Jelley, 1955). For instance, the Cerenkov threshold energy is 0.263 MeV for electron and 485 MeV for proton when the refraction index of water is 1.33.

When the target is water, the secondary charged particles under neutron irradiation are mainly recoil nuclei and secondary electron. Recoil nuclei can be generated from neutron elastic scattering and inelastic scattering. However, considering the energy range of neutrons is lower than 20 MeV in this study, and consequently the maximum kinetic energy of the recoil nuclei ($Z \geq 1$) is far lower than the Cerenkov threshold energy (>=485 MeV). The secondary electrons of recoil nuclei also do not have sufficient energy to emit Cerenkov photons according to the calculated results. The secondary electrons also can be generated by the interaction of secondary gamma rays from the neutron capture reaction. For neutron capture with hydrogen and oxygen atoms, the typical energies of the emitted gamma rays are 2.224 MeV, 0.871 MeV, 1.088 MeV, 2.184 MeV and 3.272 MeV. Therefore, the maximum energy of the consequent secondary electrons of the captured gamma ray would be higher than the threshold energy (0.263 MeV) of the generation of Cerenkov radiation. One can expect that the main cause of the Cerenkov radiation for neutron irradiation in water is the secondary electrons from the gamma ray of neutron capture reaction. Based on the cross sections of neutron capture reaction, the primary production mechanism of Cerenkov photons is the interaction effect between the medium and secondary electrons from the gamma rays generated by neutron capture with hydrogen atoms, which contributes at least 99% of total Cerenkov photon numbers according to the calculated results.

2.2. Monte Carlo simulation

Geant4 Monte Carlo package (Agostinelli et al., 2003; Allison et al., 2006) was employed to investigate the relationship between Cerenkov photons and dose deposited during neutron irradiation. The prepackaged QGSP_BIC_HP physic list with additional optical physics process was adopted in all simulations. The QGSP_BIC_HP package includes standard electromagnetic and hadronic physics processes and has been suggested for the simulation of neutron interaction for neutrons below 20 MeV (Geng et al., 2016). A cut-off value of 0.01 mm was chosen in Geant4.

In this study, a 10×10 cm^2 neutron field was employed to perpendicularly irradiate a $50 \times 50 \times 50$ cm^3 water phantom, as shown in Fig. 1. A stack of $2 \times 2 \times 0.2$ cm^3 voxels along the central axis were built to score the quantities of interest. The parameters studied in this paper include the number of Cerenkov photons, neutron dose deposited by the secondary electrons with energy higher than Cerenkov threshold (D_c) and total neutron dose (D_t). A series of neutron beam energies from 0.001 eV to 10 MeV were investigated. All simulations were performed with 10^9 primary particles.

3. Results and discussion

3.1. Dose deposition characteristic of monoenergetic neutron

In order to analyze the relation of the dose deposition characteristic and the Cerenkov radiation for monoenergetic neutron, we first calculated the ratio of the neutron dose deposited by secondary electrons with energy greater than the Cerenkov threshold energy (D_c) and the total neutron dose (D_t) for different monoenergetic neutron energies. These quantities of interest were obtained in the first scoring voxel along the central axis in order to avoiding the change of the neutron energy with the increased depth. Therefore, the dose deposition in this scoring volume was considered to be caused by the initial beam energy. The results are shown in Fig. 2.

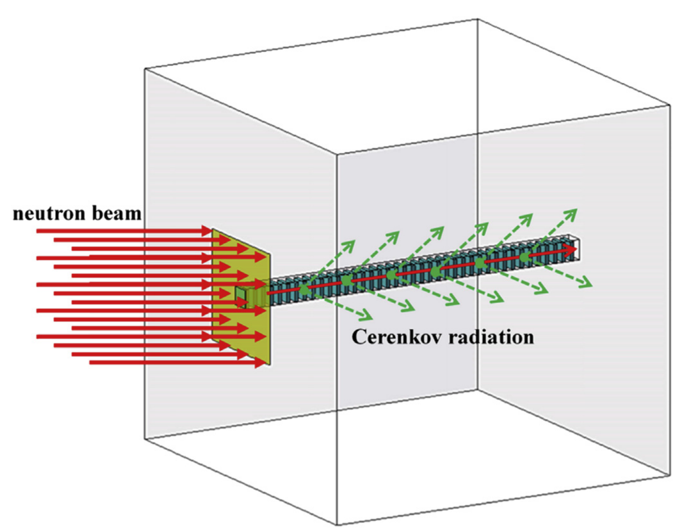

Fig. 1. Schematic of the geometry and beam setup in Monte Carlo simulations.