

Theoretical Research on A New Type of Personal Active Neutron Dosimeter

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Abstract

Due to the rise of nuclear power plants and nuclear medicine, radiation protection has become a key issue that more and more people pay attention to. In radiation protection, neutron protection has always been the focus and difficulty. In order to solve this problem, this paper proposes a new type of personal neutron dosimeter, which expands the detection range of neutrons through a three-stage structure. Through Geant4 Monte Carlo simulation software, the images of different materials, different sizes of polyethylene, Si depletion layer, and boron film on the detection efficiency were simulated, and the structure of the detector was optimized, which provided a theoretical basis for the future production of the detector. Design.

Keywords

Monte Carlo simulation; Neutron measurement; Active personal neutron dosimeter.

1. Introduction

With the increase in the number of nuclear power plants, personal radiation protection has also been paid more and more attention. [1] The detection of neutrons in radiation protection is particularly important. This article will introduce several important neutron detectors, and propose a new type of neutron detector and optimize its structure.

2. Personal Neutron Dosimeter

There are many types of personal neutron dosimeters currently on the market, among which DOS-2002 is a commercial personal neutron dosimeter developed by PTB. There is a silicon detector inside, which mainly uses the ^6LiF , polyethylene and ^{10}B covered on the surface of the detector to react with neutrons and collect secondary charged particles to collect neutrons.

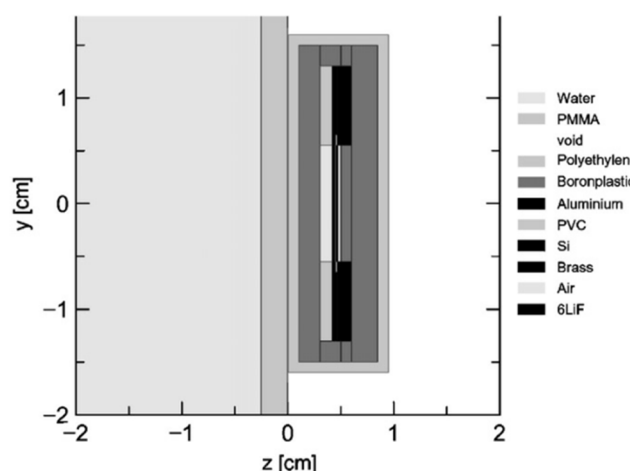


Figure 1. Internal structure of DOS-2002 detector

The neutron detector is sensitive to shock: the instrument is dropped from a height of 10cm onto a hard wooden surface 60 times (10 times per surface), which will produce a dose value of 1.2mSv.

The DOS-2002 dosimeter is sensitive to photon radiation, and it is much higher than the natural neutron background dose equivalent during background measurement. Experiments are conducted for different angles, and the results show that both 0° and 60° have large deviations at 24keV and 14.8MeV. The deviation of low energy is much larger than that of high energy.[2]

The PDM-313 personal neutron detector is a personal neutron dosimeter made by Aloka Company based on a single silicon diode. It also uses the nuclear reaction between ^6Li and neutrons to collect thermal neutrons, and uses the albedo method to detect fast neutrons. PDM-313 is designed to detect high energy neutrons.

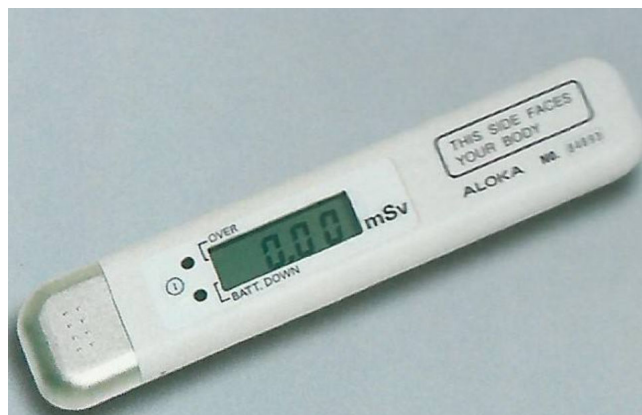


Figure 2. PDM-313 Personal Neutron Detector

According to the experimental results in the literature, it can be seen that the dosimeter performs well when the energy is 35MeV.[3]

EPD-N2 is a personal neutron dosimeter composed of three silicon detectors manufactured by Thermo Fisher Scientific. It is not sensitive to vibrations. It works normally when dropped from a height of 1.5m to the concrete floor. The angular response is $\pm 70^\circ$ and $\pm 60^\circ$, respectively.



Figure 3. EPD-N2 Personal Neutron Detector

The three silicon diodes are covered with different materials:

The first silicon diode was wrapped in a hydrogen-rich polymer layer. Neutrons reacted with the polymer to collect protons. The second silicon diode is wrapped in a ^6Li -rich material and uses ^6Li to react with neutrons to collect secondary charged particles. Nothing is wrapped

around the third diode, the purpose is to collect photons, and at the same time as a correction for the other two diodes.

3. Monte Carlo Calculation

Geant4 is used for Monte Carlo simulation calculation. The radiation source adopts a parallel irradiated surface source. In order to reduce the amount of simulation calculation, the size of the radiation source is limited to 25% larger than the personal dosimeter. The water film after the dosimeter is a standardized water film composed of water and PMMA recommended by the ISO organization. Its water-filled size is 300x300x150mm. PMMA forms an external package. The thickness of the side that fits the dosimeter is 5mm, and the thickness of the remaining three sides is 10mm. Geant4 is a calculation software based on Monte Carlo simulation method. Geant4 has a high degree of freedom. From radioactive sources, physical processes to detectors, it can be set according to your requirements to meet the simulation needs under various conditions. In addition, Geant4, as an open source program, can add external interfaces to process the simulated data. Geant4 provides more than 100 kinds of particles including electrons, protons, neutrons, etc. for users to use, and can set up a single-energy radioactive source and energy spectrum. At the same time, the program package provides material interaction types such as electromagnetic interaction, strong interaction, decay process, optical process, photolepton and hadron, parameterization process, and transport process. Geant4 has produced many extended subroutines according to needs, such as the Geant4-DNA model for cell damage and repair,^[4] which includes the reaction of particles and substances under microscopic conditions. The internal structure of the program contains different cell and protein models, which can Meet the research of microdosimetry..

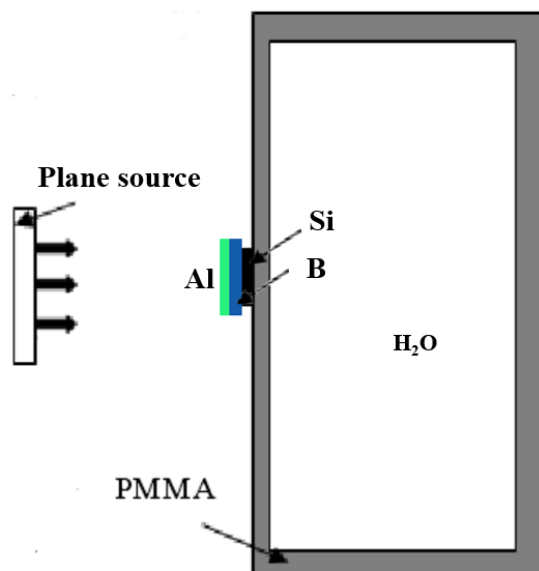


Figure 4. Geometric structure construction of personal neutron dosimeter

Construct the geometric model of the personal neutron dosimeter through Geant4, and use the chemical composition of the material to add materials to the geometric model. At the same time, a water body membrane is constructed and materials are added. The energy deposition of secondary charged particles produced after neutrons pass through a personal dosimeter is recorded. At the same time, explore the influence of different sizes and different materials on neutrons and secondary charged particles, and then determine the geometry and material parameters of the personal neutron dosimeter to provide a theoretical basis for future designs.

Geant4 can continue to record the particle information entering it by setting the sensitive volume of the detector. It can be refined to the track and energy deposition of each particle, and the distribution of the particles can be explored by analyzing the collected information, thereby optimizing the structure of the detector.

4. Calculation Results and Discussion

There are two difficulties in neutron measurement. The first is that the neutron is not charged. The measurement of neutron requires the use of secondary charged particles produced by the reaction of neutron and matter. The second is that the energy range of neutrons is relatively wide, and there are often problems of fewer channels in the process of neutron spectrum decoding.

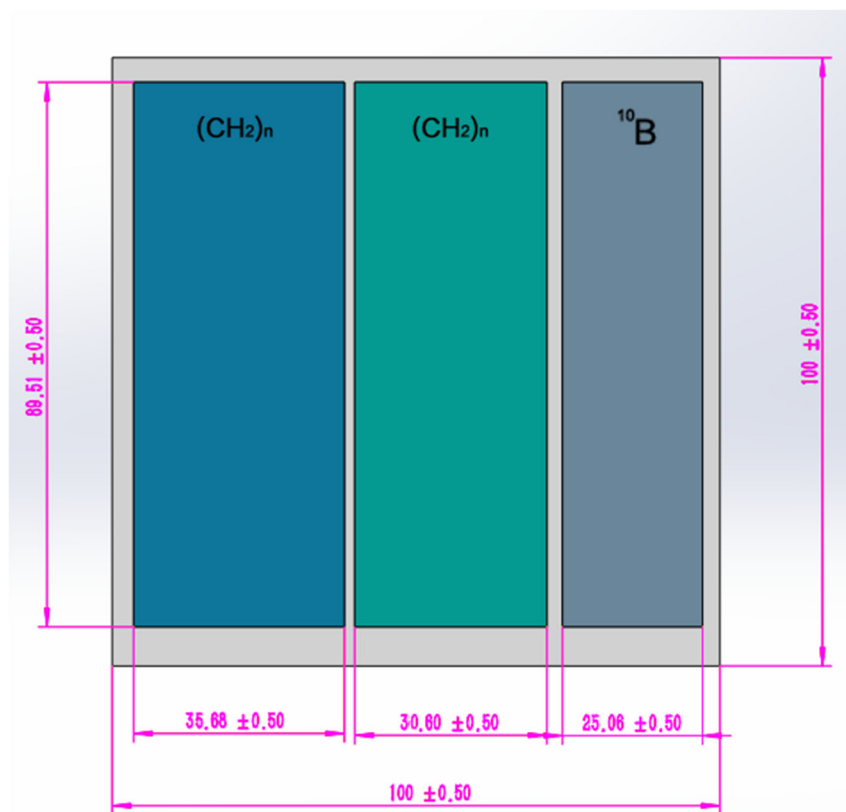


Figure 5. The structure of personal neutron dosimeter

Based on these two points, this paper designs a personal neutron dosimeter based on a three-layer structure, using boron as the reaction medium, polyethylene as the moderating medium, using different thicknesses of polyethylene to detect neutrons of different energies, and using Si at the same time. As a collector, it detects the secondary charged particles generated. Different from the existing personal neutron dosimeters, in addition to the structure, two functions of active alarm and dose display are also designed. Combined with the embedded system, different users can set the threshold for different environments. The collected electrical signals enter the electronic system for judgment, and signals that exceed the threshold will be alarmed. In addition, a communication serial port based on the UDP network protocol is set up in the electronics system, which can interact with the host computer, transmit and process the data of multiple personal neutron dosimeters, and facilitate subsequent management.^[5]

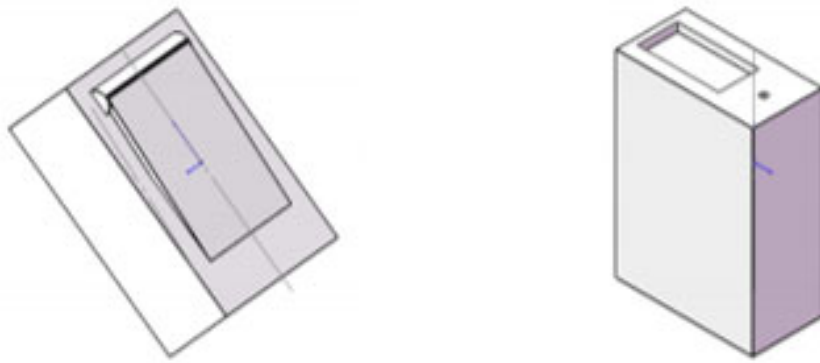


Figure 6. Geometry of active personal neutron dosimeter

In order to determine the choice of each parameter, Geant4 is used for simulation, and the simulation results are shown below.

4.1. Selection of Boron Film Material and Thickness

The first is the choice of boron. As the reaction medium of neutrons, boron reacts with neutrons to produce ${}^7\text{Li}$ and alpha particles. The reaction efficiency of boron and neutrons is used as the main parameter for selecting the boron film. It includes two parameters that may affect the efficiency of neutron detection. One is the abundance of boron material and the other is the thickness of the boron film. Based on the usage scenarios of the personal neutron dosimeter, the neutrons in the thermal neutron energy region are used for simulation. Set up a Gaussian distribution plane neutron source, 10mm away from the boron geometry. In order to prevent the surrounding environment from interfering with the detection process, it is set to low-density air. The neutron detection efficiency of natural boron in daily environment and high-abundance boron with an abundance of 0.96 are simulated respectively. Simultaneously simulate the influence of different boron film thickness on neutron detection, and the simulation results are shown in the figure below.

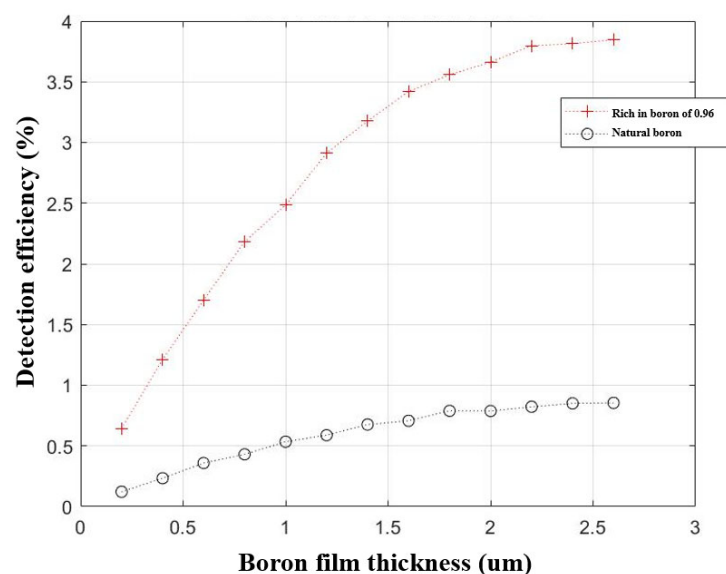


Figure 7. Different parameter boron film and neutron detection efficiency

It can be seen from the results that the detection efficiency of boron and neutrons of different demeanors has a large gap. In the case of the same boron film thickness, the neutron detection efficiency of boron with an abundance of 0.96 is 2-4 times higher than that of natural boron. Explore the reason for the high content of boron in high-abundance boron, which is more likely to occur with neutrons, which leads to a significant improvement in neutron detection efficiency. Compare the influence of boron films of different materials on neutron detection efficiency. The necessity of choosing high-abundance boron.

It can also be seen from the results that as the thickness of the boron film increases, the efficiency of neutron detection continues to increase. When the thickness of the boron film exceeds 2 μm , the detection efficiency basically does not change, and the neutron collection efficiency basically reaches saturation. So choose 2 μm as the thickness of the boron film used in the detector.

4.2. Si Depletion Layer Selection

After determining the material and size of the boron film, a simulation is performed on the Si depletion layer that receives the signal. First, by simulating the size of different Si depletion layers, the influence on the neutron deposition energy is determined. The geometric model and physical structure are the same as when simulating the boron film, but the difference lies in the composition of the sensitive body material. First, the effect of different sizes of Si depletion layer on the neutron deposition energy is simulated, and the results are as follows:

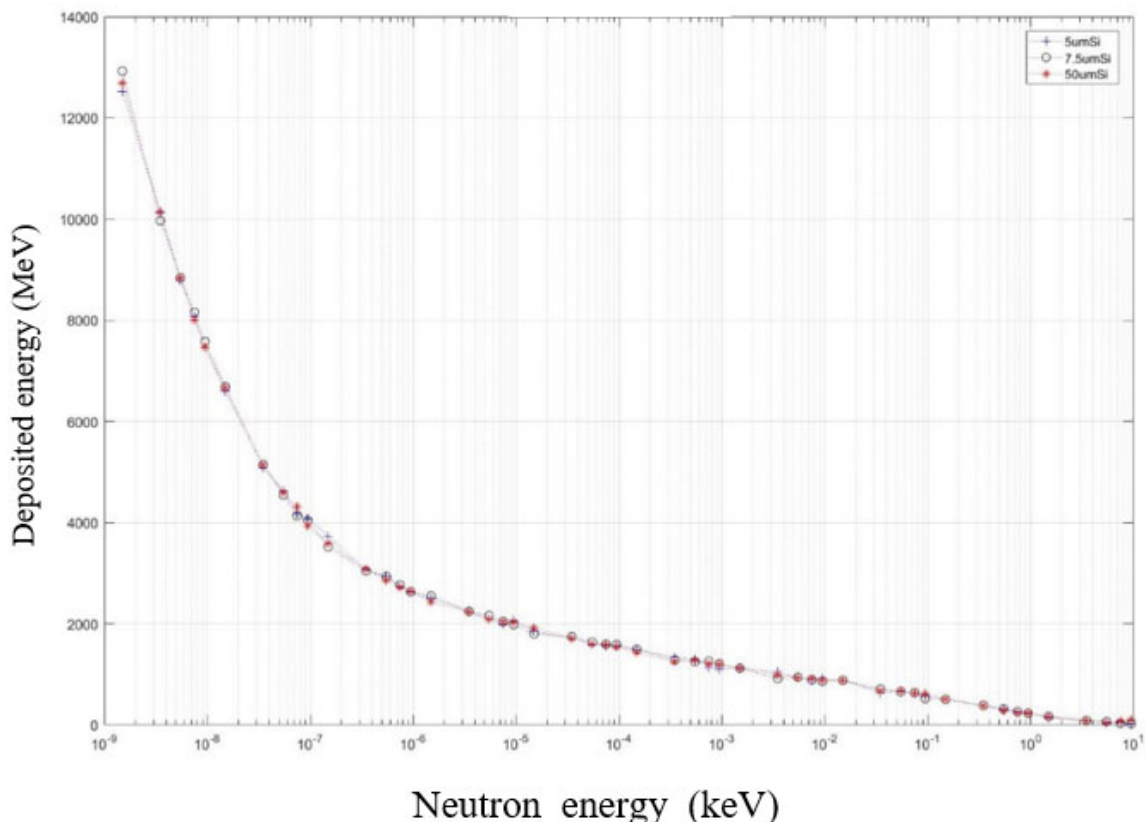


Figure 8. Influence of Si Depletion Layers with Different Sizes on Neutron Deposition Energy

It can be seen from the results that the size of the Si depletion layer has no effect on the neutron deposition energy, so from this aspect, any size of depletion layer can be selected. Next, simulate

the photon energy deposition after ^{60}Co passes through the detector, and the simulation results are as follows:

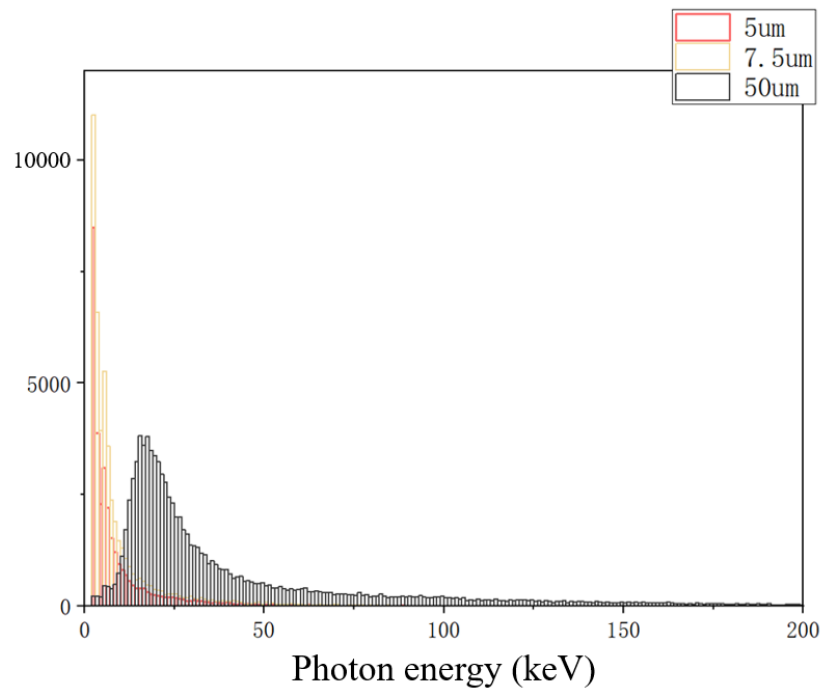


Figure 9. Photon energy deposition

After ^{60}Co irradiates the detector, the collected photon energy is deposited. From the results, it can be seen that as the thickness of the Si depletion layer increases, the photon deposition energy is also increasing. Finally, 50um was chosen as the thickness of the Si depletion layer. After determining the thickness of the depletion layer, the detection efficiency is optimized by setting a threshold.

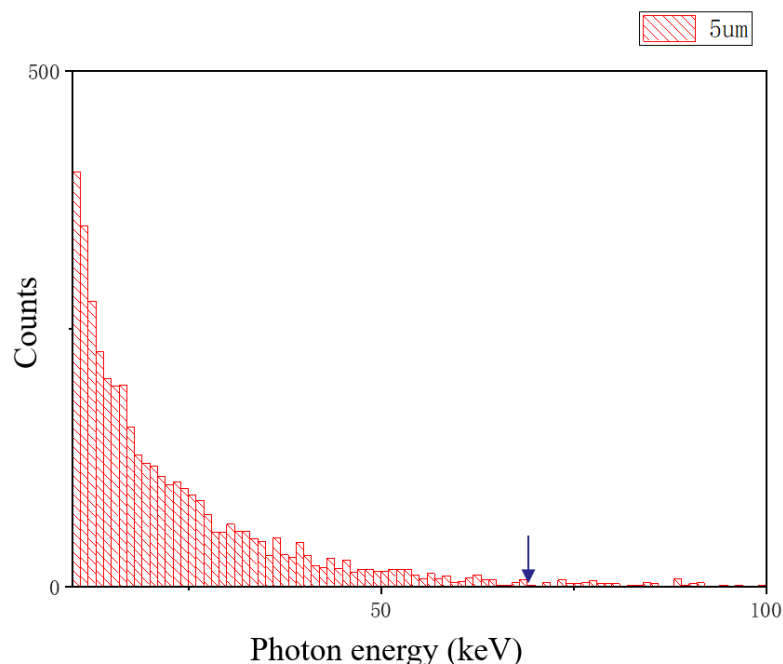


Figure 10. The influence of 50umSi depletion layer on photon deposition energy

In order to reduce the impact of photon energy deposition on neutron measurement, a Si depletion layer with a thickness of 5 μ m is selected. Figure 10 is also the photon energy deposition collected after ^{60}Co irradiating the detector. You can choose 70keV as the threshold, and consider that less than 70keV is the photon count. To further reduce the impact of photon energy deposition on neutron measurement.

4.3. The Choice of Polyethylene Film

The final step is to determine the thickness of the polyethylene film. Under the same experimental conditions, change the material of the sensitive body to simulate the reaction efficiency of different energy neutrons in different sizes of polyethylene. The simulation results are shown in the figure below.

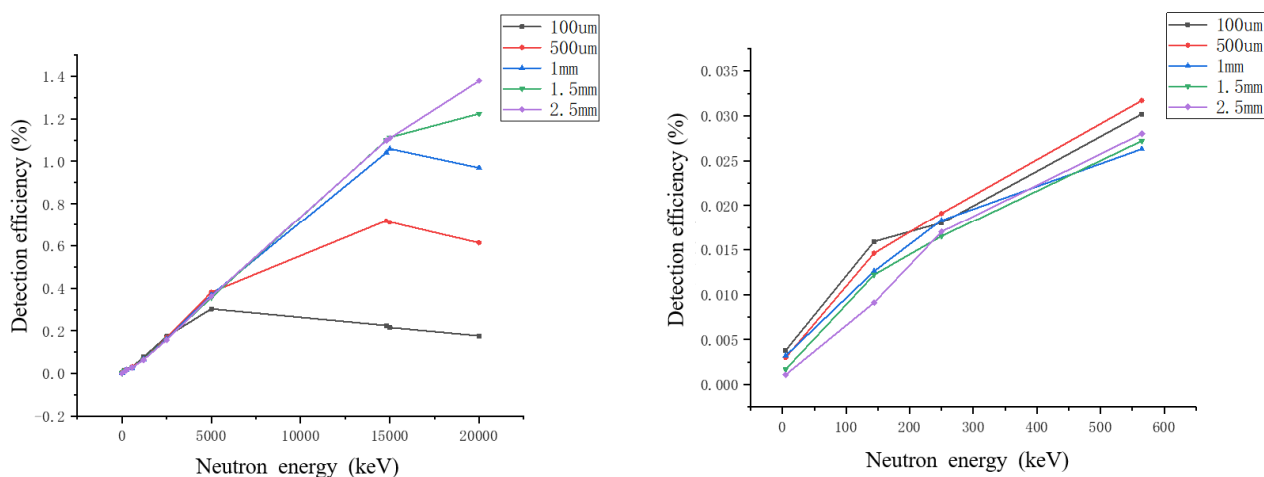


Figure 11. Detection efficiency of different sizes of polyethylene film

It can be seen from the results that the size of the polyethylene in the low-energy section has little effect on the detection efficiency. In the high-energy section, the detection efficiency of the polyethylene increases as the size of the polyethylene increases.

5. Conclusion

This article introduces the method of neutron detection through literature research and provides the personal neutron dosimeters that are currently used in the market. This paper proposes a new type of personal neutron dosimeter based on a three-layer distribution structure. On the basis of the original neutron dosimeter, the detection range of neutrons is expanded by adding different polyethylene sizes. The effects of boron film, Si depletion layer, polyethylene size and material on detection efficiency are provided through simulation. Provide a theoretical basis for the production of dosimeters in the future.

References

- [1] Liu Xiaoyong, Tan Jianming, Huang Yongshun, Huang Jian, Jiang Jiabin, Lai Guanchao. Investigation and analysis of residents' perception of nuclear radiation risk in the location of a newly operating nuclear power plant[J]. Chinese Radiological Health, 2020, 29(03):281-284.
- [2] Luszyk-Bhadra M, Nakhostin M, Niita K, et al. Electronic personal neutron dosimeters for energies up to 100 MeV: Calculations using the PHITS code[J]. Radiation Measurements, 2008, 43(2-6):1044-1048.
- [3] Luszyk-Bhadra M. Compliance of electronic personal neutron dosimeters with the new International Standard IEC 61526[J]. Radiation Protection Dosimetry, 2007, 125(1/4):15-18.

- [4] Chen Junliang, Yun Sujun, Dong Tiekuang, Ren Zhongzhou, Zhang Xiaoping. Investigate the radiation-induced damage on an atomistic DNA model by using Geant4-DNA toolkit[J]. Nuclear Inst. and Methods in Physics Research, 2021,B:494-495.
- [5] Takada Masashi, Nunomiya Tomoya, et al Development of a real-time neutron beam detector for boron neutron capture therapy using a thin silicon sensor.[J]. Applied radiation and isotopes : including data, instrumentation and methods for use in agriculture, industry and medicine, 2021, 176.