Optimization of water-pumping-injection multi-homocentric sphere neutron spectrometer

Yujie Qiao¹ · Jianbo Yang¹ · Jie Xu¹ · Rui Li¹ · Keliang Mu²

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Abstract

The self-developed pumping water multi-layer concentric neutron spectrometer response function exists a ladder shape, which is not conducive to the subsequent neutron spectrum. The FLUKA program is used to optimize the structure of the multi-layer concentric sphere neutron spectrometer. The response functions of stainless steel, aluminum, lead and leaded glass (divided into sandwich and double-layer combination) to the ³He detector were obtained by simulating the inner shell materials with energy in the interval of 0.01 eV–1 GeV. The results show that when the shell material is aluminum and lead glass, the response function does not appear stepped, and the response functions of the other materials appear stepped. Therefore, the use of aluminum and lead glass instead of stainless steel as the casing of the pumped water multi-layer concentric neutron spectrometer can make its energy spectrum measurement more accurate.

Keywords Water-injection multi-sphere neutron spectrometer · Fluence energy response · Optimized design · Aluminium case

1 Introduction

The neutron radiation environment in space is complex, and the neutron energy is complicated which is ranging from eV to GeV [1, 2]. Currently, a multi-sphere neutron spectrometer is mainly used to monitor the neutron dose equivalent (rate). The multi-sphere neutron spectrometer, also called Bonner ball, was proposed by Bonner in 1960 [3]. Due to its low resolution, but wide measurement range, isotropy, and easy measurement, so it is often used for neutron spectrum measurement [4–8]. Conventional multi-sphere neutron spectrometers are more sensitive to neutrons with energy below 20 MeV and have almost no response to neutrons with energy above 20 MeV. Therefore, high-energy neutrons may cause dose underestimation [9–11]. Birattori developed the LINUS meter, enabling it to be used for neutron radiation field measurements at 400 MeV. Afterward, the researchers improved the

structure of the instrument and designed single-ball multi-count neutron spectrometers, rotating multi-sphere neutron spectrometers, and use water and boric acid as moderating materials for the neutron spectrometer [12–16]. But these multi-sphere neutron spectrometers all have certain problems such as a large number of slowing balls, inconvenient to carry, and possible ball interference in the measurement process [17, 18]. Therefore, for the conventional multi-sphere neutron spectrometer, our team designed a pumped water multi-sphere neutron spectrometer [19–24]. The aim is to solve the problem of the low sensitivity of high-energy neutrons, and to solve problems such as ball interference, making it more portable.

The pumped water multi-layer concentric neutron spectrometer uses 304 stainless steel as the casing material of the detector which will cause some problems. For example, stainless steel material leads to mass increase and the response function is not solved accurately. Therefore, the

✉ Jianbo Yang, yjb@cdut.edu.cn | ¹Chengdu University of Technology, Chengdu 610059, China. ²Nuclear Power Institute of China, Chengdu 610014, China.

focus of this paper is to study the influence of stainless steel shell on the detector response function, and to find a more excellent shell material to improve the accuracy of the detector measurement of pumping and injecting multilayer concentric spherical neutron spectrometer.

2 Materials and methods

2.1 Water-injection multi-sphere neutron spectrometer

The structure of the pumped water multi-layer concentric neutron spectrometer is shown in Fig. 1 [19–24]. The overall structure of the spectrometer is a multi-layer concentric spherical shell made of 304 stainless steel with a maximum diameter of 45.6 cm, and the thickness of each layer of 304 stainless steel is 3 mm. A 2705 type ^3He proportional counter (Built-in air pressure of 10 atmospheres) manufactured by LND company is placed in the center. By pumping 5 water layers, 32 kinds of water layer thickness variation schemes can be designed. According to the difference of the neutron moderating ability of different water layer thicknesses, the relationship between the counting rate response of the thermal neutron detector and the neutron energy spectrum was analyzed to obtain the incident neutron spectrum. In addition, in order to measure high-energy neutrons, a layer of lead auxiliary material has been added to the spectrometer. The water layer combination method uses binary for mnemonic, 1 means there is water and 0 means no water. For example: 10Pb010 indicates that the first and the fourth layers have water, Pb means the lead layer, and the other layers are empty. The minimum mass of the spectrometer is 53.79 kg (no water) and the maximum mass is 97.64 kg (full water).

2.2 Calculation of response function of pumped water multi-layer concentric neutron spectrometer

The size of the neutron surface source directly affects the calculation of the response function of the pumped water multi-layer concentric neutron spectrometer. So when calculating the neutron energy response function of the detector, it is assumed that the incident neutron beam is a parallel single energy beam, and the cross-section is circular. For a moderator layer combined with a diameter d cm of the outermost moderator material, a ^3He proportional counter with a volume of the V is placed in the center, then the formula for the fluence energy response of the moderator layer combination is [25]:

$$R_d(E) = \frac{M}{\Phi(E)} \quad (1)$$

In the formula, $R_d(E)$ is the response function when the maximum diameter of the moderator combination is d cm, M is the neutron detector count and $\Phi(E)$ is the neutron fluence with energy E . When using FLUKA to calculate the response function of the detector, assuming that the protons generated in the ^3He sensitive volume are all recorded. Using the RESNUCLEi card to record the number of P(proton) or T(tritium) produced by the ^3He (n, p) T reaction in the ^3He sensitive volume, that is $N_{p\text{ and }T}$. The corresponding energy response value can be obtained [8]:

$$R_d(E) = \frac{\pi \times d^2}{8} \times N_{p\text{ and }T} \quad (2)$$

The response function of 18 water layers is calculated, as shown in Fig. 2. The results showed that, for water layer combinations of 00Pb000, 01Pb000, 10Pb000, 11Pb00, there is a peak in the 10^{-2} – 10^{-1} MeV interval.

Fig. 1 Pumping water-type multi-layer concentric neutron spectrometer model

Fig. 2 Pumping water multi-layer concentric neutron spectrometer response function (18 water layer combinations)

2.3 Sandwich structure and double layer structure model

For the response function of a multi-layer concentric spherical neutron spectrometer with pumping water, the peak value exists at 10^{-2} – 10^{-1} MeV, the FLUKA program was used to simulate the effect of different metal materials on the neutron fluence energy response under different thickness. The simulation model is shown in Fig. 3: (a) is a ^3He spherical proportional counter in the center of the sandwich structure, 3 cm thick water layer, 1 cm metal material (lead, stainless steel, aluminum), 2 cm thick water layer; (b) is a double-layer structure with a variable thickness of the water layer and auxiliary materials.

3 Results and discussion

3.1 Influence of sandwich combinations

According to the model in Fig. 3a, the influence of 304 stainless steel (SS), Pb, Lead Glass, Al and Al_2O_3 as auxiliary materials on the response function of the thermal neutron detector is simulated using FLUKA as shown in Fig. 4. In Fig. 4, when the neutron energy is 10^{-8} – 10 MeV, Pb and Lead Glass as an auxiliary material does no effect on the response of the thermal neutron detector with the increase of thickness. With the increase of Pb thickness in the energy range of 10 MeV–1 GeV, the neutron fluence energy response of the thermal neutron detector gradually increases. The main reason is that inelastic scattering is mainly after 10 MeV, while the elastic scattering of lead is very low before 10 MeV. For stainless steel as auxiliary materials, the neutron injection response of the thermal neutron detector in the energy range of 10^{-8} –1 MeV

Fig. 3 A simulated structure of the effects of metallic materials on neutrons: **a** sandwich structure; **b** double layer structure

Fig. 4 Effect of Pb, stainless steel (SS), lead glass, Al and Al_2O_3 as auxiliary materials on the response of neutron detectors

gradually decreases with the increase of thickness, but it gradually increases in the energy range of 10^{-1} – 10^3 MeV. But neither Al nor Al_2O_3 affects the detector's response function.

3.2 The effect of the two-layer combination

According to Fig. 3b model, FLUKA was used to simulate the influence of the thickness of the lower water layer and the auxiliary material on the detector response function. The simulation results are shown in Fig. 5. Under the double-layer combination, when the auxiliary material is stainless steel, the response function of the central thermal neutron detector has a peak value when the middle energy is 10^{-2} – 1 MeV, no matter the thickness of the water layer or the thickness of the stainless steel increases. When the auxiliary material is Pb and Lead Glass, no matter how the water layer changes, the response function

of the thermal neutron detector is always in the smooth phase throughout the energy range (10^{-8} – 10^3 MeV), and no breakpoint appears. Therefore, the stainless steel under the double-layer combination will not only reduce the response function of the thermal neutron detector in the energy range of 10^{-8} – 10^{-2} MeV, but also cause the phenomenon of the response function to increase in the energy range of 10^{-2} – 1 MeV. But Al and Al_2O_3 have no effect on the detector response function.

3.3 Improved response function of pumped water multilayer concentric neutron spectrometer

According to the structural model of the detector in Fig. 1, the response function of the detector was simulated when the stainless steel shell was replaced with aluminum and lead glass by the pumped water multi-sphere neutron spectrometer. As shown in Fig. 6, compared to stainless

Fig. 5 Effect of thickness change of the water layer and auxiliary material thickness on the detector response under double-layer structure

steel, aluminum and lead glass to improve the detector response function between 10^{-8} and 1 MeV. The response function of the aluminum shell has a small peak in the range of 10^{-2} – 10^{-1} MeV, but it is greatly reduced compared to the stainless steel shell; the lead glass shell has basically no peak in the energy range of 10^{-2} – 10^{-1} MeV, and the lead glass has a detector response between 10 MeV and 1 GeV slightly higher than the case due to the lead content in the lead glass.

4 Conclusion

In this paper, the effects of aluminum, aluminum oxide, lead glass, 304 stainless steel, and their constituent materials on the response function of the ^3He detector are

simulated by Monte Carlo methods. The following main conclusions are drawn:

1. Aluminum and aluminum oxide do not affect the response function of the detector under the double-layer combination and sandwich combination, while lead glass only increases the detector's response function value to high-energy neutrons.
2. Aluminum, aluminum oxide and lead glass as the shell of the multi-layer concentric sphere neutron spectrometer pumped with water will make the response function of the detector smoothly, thereby making its energy spectrum measurement more accurate.
3. 304 stainless steel and its constituent materials will make the detector response function step-like under the double-layer combination, and its value will be

Fig. 6 Response function of pumped water multi-sphere neutron spectrometer after changing spherical shell

affected under the sandwich combination, which mainly manifests as the value decreases in the energy range of 1 eV–1 MeV. And in the energy range of 10 MeV–1 GeV, the internal value increases.

- Two improvement directions are provided for the pumped and injected multi-layer concentric spherical neutron spectrometer in the future, aluminum shell is used to replace the stainless steel shell as the supporting material, and the built-in structure of the spectrometer does not change.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Zhang ZX, Wei ZY, Fang MH (2009) Neutron radiation effects of space environment and measurement technique. Equip Environ Eng 6(4):5–11 (in Chinese)
- Goldhaden P, Reginatto M, Kniss P (2002) Measurement of energy spectrum of cosmic-ray induced neutrons aboard an ER-2 high altitude airplane. Nucl Instrum Methods Phys Res A 476:42–45. [https://doi.org/10.1016/S0168-9002\(01\)01386-9](https://doi.org/10.1016/S0168-9002(01)01386-9)
- Bramblett LR, Ewing IR, Bonner WT (1960) A new type of neutron spectrometer. Nuclear Instrum Methods 9(1):1–12. [https://doi.org/10.1016/0029-554X\(60\)90043-4](https://doi.org/10.1016/0029-554X(60)90043-4)
- Khabaz R, Hakimabad HM (2011) Measurement of the neutron spectrum by the multi-sphere method using a BF₃ counter. Nucl Technol Radiat Prot 26(2):140–146. <https://doi.org/10.2298/NTRP1102140K>
- Khabaz R, Hakimabad HM (2011) Determination of ²⁴¹Am–Be spectra using bonner sphere spectrometer by applying shadow cone technique in calibration. J Appl Sci 11(15):2849–2854
- Khabaz R, Hashem Miri S (2011) Development of a Bonner sphere spectrometer with emphasis on decreasing the contribution of scattering by using a new designed shadow cone. J Radioanal Nucl Chem 289(3):789–794. <https://doi.org/10.1007/s10967-011-1141-8>
- Huang H, Yang JB, Tuo XG et al (2017) A new three-tier architecture design for multi-sphere neutron spectrometer with the FLUKA code. Mod Phys Lett B 30(19):1–10
- Chang K (2019) Research on spectrum reconstruction technic for water-pumping-injection multi-sphere neutron spectrometer. Dissertation. Chengdu University of Technology (in Chinese)
- Lee KW, Sheu RJ (2017) Comparing two measurements of the same cosmic-ray neutron spectrum using standard bonner spheres and spheres and high-sensitivity bonner cylinders. Radiat Prot Dosim 177(4):450–457. <https://doi.org/10.1093/rpd/ncx063>
- Lee KW, Sheu RJ (2015) Spectral correction factors for conventional neutron dosimeters used in high-energy neutron environments. Radiat Prot Dosim 164(3):210–218. <https://doi.org/10.1093/rpd/ncu298>
- Gómez Ros JM, Bedogni R, Moraleda M et al (2012) Designing an extended energy range single-sphere multi-detector neutron spectrometer. Nucl Instrum Methods Phys Res Sect A (Accel Spectrom Detect Assoc Equip) 677:4–9. <https://doi.org/10.1016/j.nima.2012.02.033>
- Khabaz R (2012) Study of a new multi-sphere spectrometer based on water moderator with a high efficiency ⁶LiI (Eu) detector. J Radioanal Nucl Chem 293(1):383–389. <https://doi.org/10.1007/s10967-012-1748-4>
- Ing H, Clifford T, Mclean T et al (1997) ROSPEC—a simple reliable high resolution neutron spectrometer. Radiat Prot Dosim

- 70:273–278. <https://doi.org/10.1093/oxfordjournals.rpd.a031959>
14. Khabaz R, Hakimabad HM (2011) Evaluation of response matrix of a multisphere neutron spectrometer with water moderator. *Pramana J Phys* 77:599–609. <https://doi.org/10.1007/s12043-011-0138-8>
 15. Ueda H, Tanaka H, Sakurai Y (2015) The improvement of the energy resolution in epi-thermal neutron region of Bonner sphere using boric acid water solution moderator (reprinted). *Appl Radiat Isot* 106:107–110. <https://doi.org/10.1016/j.apradiso.2015.10.010>
 16. Chen R, Chen J, Xu YJ et al (2018) Design of an improved multi-sphere neutron spectrometer based on boron-doped moderator. *Chin J Radiol Health* 27:148–152 **(in Chinese)**
 17. Li TS, Fang D, Li H (2007) A Monte Carlo design of a neutron dose-equivalent survey meter based on a set of ^3He proportional counters. *Radiat Meas* 42(1):49–54. <https://doi.org/10.1016/j.radmeas.2006.08.001>
 18. Chernyaev A, Gaponov I, Kazennov A (2004) Direct methods for radionuclides measurement in water environment. *J Environ Radioact* 72(1):187–194. [https://doi.org/10.1016/s0265-931x\(03\)00201-7](https://doi.org/10.1016/s0265-931x(03)00201-7)
 19. Yang JB (2017) Design of multi-phase concentric spherical neutron energy spectrum instrument for pumping water, Chengdu **(in Chinese)**
 20. Yang JB, Tuo XG, Huang H et al (2016) The utility model relates to an automatic multi-sphere neutron spectrometer for water injection and drainage. CN205581310U **(in Chinese)**
 21. Yang JB, Tuo XG, Huang H et al (2018) Water injection and drainage automatic multi-sphere neutron spectrometer and measurement method. ZL 201610264803.7 **(in Chinese)**
 22. Yang JB, Tuo XG, Wang HH et al (2019) Pumping water multi-layer concentric ball device and neutron energy spectrum detection system. ZL 201710201494.3 **(in Chinese)**
 23. Yang JB, Tuo XG, Li R et al (2020) Multi-channel single pump pumping water device, system and method thereof. ZL 201810497605.4 **(in Chinese)**
 24. Yang JB, Tuo XG, Cheng Y et al (2018) Water pumping and injecting multi-layered concentric sphere neutron spectrometer. US2018/0224565A1
 25. Howell RM, Burgett EA, Wiegel B, Hertel NE (2010) Calibration of a Bonner sphere extension (BSE) for high-energy neutron spectrometry. *Radiat Meas* 45(10):1233–1237. <https://doi.org/10.1016/j.radmeas.2010.09.003>

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