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Design of Water Body *α* and *β* Complex Detectors

Xin Huang*, Liangquan Ge, Guoqiang Zeng, Jiao Liu

College of Applied Nuclear Technology and Automation Engineering, Chengdu University of Technology, Chengdu, China
Email: *huangxin_cdut@163.com

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Abstract

The range of natural radioactive *α* particles in water in ZnS(Ag) and the semi-absorbent thickness of *β* particles in plastic scintillators were calculated by theoretical formula and used as the thickness of ZnS(Ag) and plastic scintillators respectively. The energy deposition curves of *β* particles and *γ* photons with different energies in plastic scintillator were obtained by Monte Carlo simulation, and the optimal thickness of ZnS(Ag) and plastic scintillator were obtained. The preliminary design of the composite detector was completed. The results show that the thickness of ZnS(Ag) is 30 μm and the thickness of plastic scintillator is 1 mm.

Subject Areas

Nuclear Physics

Keywords

Semi-Absorption Thickness, Composite Detectors, Transmission Ratio, Monte Carlo, Energy Deposition

1. Introduction

Direct measurements of *α* and *β* particles in the water can initially determine the pollution level of the water. With the development of the economy, people are more concerned about their own health, while the pollution caused by industrial development and radioactive waste disposal attracts more attention. Due to the low natural radioactive activity in water, the indirect measurement method is mostly adopted for the measurement of *α* and *β* particles in water, which is complicated in sample preparation and not strong in real-time. In China, a large-area thin window, multi-filaments and flow-gas proportional counter are also used to directly measure the *α*/*β* particles in water [1], but the high pressure needs to be adjusted to realize the measurement of α/β particles. In this paper, a composite detector composed of ZnS(Ag) and plastic scintifier is directly placed above the unprocessed water sample to be tested to directly measure the radioactivity of α/β in the water, which has the advantage of avoiding contamination and modification of sample preparation efficiency in the sample preparation process, and can be monitored online [2]. On the other hand, theoretical calculation and Monte Carlo simulation were used to determine the thickness of ZnS(Ag) and plastic scintillator, which provided theoretical and technical support for the later work.

2. Overall Design of Composite Detector

Since the range of α particles in natural water is 20 μm - 100 μm and the maximum range of β rays is 2 cm [3], the composite detector designed in this paper is a plastic scintifier coated with a certain thickness of ZnS(Ag) coating on the surface to achieve the simultaneous detection of α/β particles [4]. Plastic scintillator thickness is determined mainly by β particle detection efficiency and γ photon transmittance. On the other hand, by adding a second layer of plastic scintillator, the effect of γ photon on α particle detection results was removed by an anti-coincidence system.

In **Table 1**, the first layer of the composite detector is *waterproof film* to prevent impurities in water from sticking to the detector surface and causing pollution to the detector surface. The second layer ZnS(Ag) is used for α particle detection and absorption; The third layer is *plastic scintillator*, which is mainly used for the detection of β particles. The fourth layer is *PMMA photoconductivity*, which collects the photons generated in the ZnS(Ag) layer and the plastic scintillator layer, and transmits the collected photons to the photomultiplier tube. The fifth layer is the *light-reflecting coating* to increase the readout of the fourth layer of photons; the sixth layer is a *plastic scintillation* layer used for electron anticoincidence processing of γ photons.

3. Determination of the Thickness of Composite Detector

The mass thickness of the ZnS(Ag) coating and the thickness of the plastic scintillators in the composite detector will affect the detection efficiency of α and β particles [5]. In this paper, the mass thickness of ZnS(Ag) coating and the thickness of plastic scintillator are obtained by theoretical calculation and Monte Carlo simulation.

Table 1. Overall design of the composite detector.

Plastic scintillator 1 mm
Avoid light coating
PMMA Optical
Plastic sintillator (thickness: 1 mm)
ZnS(Ag) coating (thickness: 30 μm)
Waterproof membrane

Common radiative α particle nuclides in water include ^{226}Ra, ^{232}Th and their decay products, which are mainly derived from radioactive pollutants discharged from nuclear industry production and rare earth mining and smelting, such as uranium, thorium, radium and a series of their daughters [6].

The theoretical calculation formula of the range of α particles in water and ZnS(Ag) [7]:

$$R(\text{cm}) = 0.56E_\alpha \left(E_\alpha < 4\,\text{MeV}\right) \tag{2.1}$$

$$R(\text{cm}) = 0.318E_\alpha^{1.5} \left(4\,\text{MeV} < E_\alpha < 7\,\text{MeV}\right) \tag{2.2}$$

$$R(\text{cm}) = 3.2\times10^{-4}\frac{R_a\sqrt{A}}{\rho} \tag{2.3}$$

Formula 2.1 is the calculation formula for the range of α particles when the energy in air is less than 4 MeV, and Formula 2.2 is the calculation formula for the range of α particles when the energy in air is within 4 MEV - 7 MEV. Formula 2.3 is the conversion formula for the range of α particles in other substances, where R_a is the range in air, A is the atomic number of the element constituting the substance, and ρ is the density of the substance. The range of particles with different energy in the air can be obtained by formula 2.1 and formula 2.2, and it can be substituted into formula 2.3 to calculate the range of particles in the water, as shown in **Table 2**.

In **Table 2**, the maximum energy of α particles emitted by ^{226}Ra in water is 4.761 Mev. The range of α particles in ZnS(Ag) is 26.113 μm, and the ZnS(Ag) coating has very low absorption of β particles, and the ZnS(Ag) coating has a thickness of 30 μm to ensure the absorption of natural radioactive α particles in water. The energy deposition of γ photons in ZnS(Ag) is ignored due to their high penetrability. The curves of transmittance of β particles with different energies through ZnS(Ag) coating are shown in **Figure 1**.

The total β particles in the water are derived from the decay of nuclides such as ^{40}K, ^{90}Sr, ^{137}Cs and ^{129}I [7]. The extrapolation formula of the particle range is as follows [7]:

$$\mu_m = \frac{22}{E_\beta^{1.33}} \tag{2.4}$$

$$R = 0.693/\mu \tag{2.5}$$

Table 2. Main sources and ranges of particles in water.

Element	Decay	Energy/MeV	Air range/cm	Underwater range/μm	Range in ZnS(Ag)/μm
Ra-226	α	4.761	3.290	33.292	26.113
U-234	α	4.756	3.240	32.786	25.716
Th-230	α	4.66	3.150	31.876	25.001
U-238	α	4.169	2.600	26.310	20.636
Th-232	α	3.933	2.500	25.298	19.843

In Formula 2.4, E is the energy of β particles, whose unit is MeV, μ_m is the mass absorption coefficient of particle in matter in cm^2/g. Is the absorption coefficient of particles in matter. R is the semi-absorptive thickness of β particles in the substance. The semi-absorption thickness of β particles in water in plastic scintillator is calculated by the above formula, as shown in Table 3.

As shown in Table 3, the maximum energy of β particles of the natural nuclide in the water is 2.288 MeV, and the semi-absorption thickness of the plastic scintillator is 0.095 cm. Therefore, the thickness of the plastic scintillator is determined to be 1 mm, which can ensure the saturation thickness of the absorption of β particles and reduce the energy deposition of γ photons. The transmission of β particles with different energies after passing through a 1 mm plastic scintillator is obtained through calculation, as shown in Figure 2.

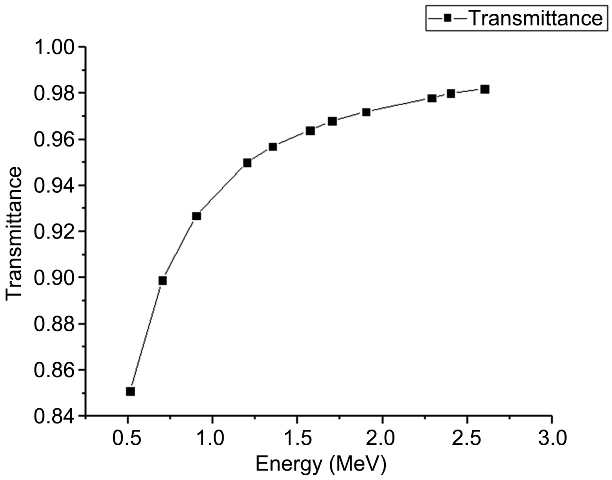

Figure 1. Transmission ratio of beta rays after passing through ZnS(Ag) coating.

Table 3. Main sources of particles in water and their range in plastic scintillator.

Element	Decay	Energy/MeV	Absorption coefficient of plastic scintillator	The semi-absorptive thickness of a plastic scintillator/cm
Sr-90	β	0.196	192.186	0.004
Sr-90	β	2.288	7.317	0.095
Cs-137	β	1.576	12.014	0.058
Cs-137	β	0.512	53.643	0.013
Cs-137	β	0.174	225.160	0.003
Cs-137	β	0.300	109.107	0.006
Cs-137	β	0.416	70.636	0.010
I-129	β	0.409	72.249	0.010
I-129	β	1.176	17.733	0.039
K-40	β	1.350	14.760	0.047
K-40	β	0.560	47.570	0.015

As shown in **Figure 2**, the transmission ratio of β particles with the energy of 2.288 MeV released by ^{90}Sr was significantly lower than 50% after passing through 1 mm plastic scintillator. Therefore, the plastic scintillator thickness of 1 mm can achieve the effective absorption of natural radioactive β particles in water. However, 1 mm plastic scintillator may produce certain energy deposition on γ photons. In order to verify the rationality of plastic scintillator thickness design, the transmission ratio of low-energy γ photons passing through 1 mm plastic scintillator was calculated, and the projection of γ photons passing through 1 mm plastic scintillator was obtained, as shown in **Figure 3**.

As shown in **Figure 3**, the transmission ratio of γ photons emitted in ^{137}Cs with an energy of 0.283 MeV reached more than 98.3%, indicating that the energy of 1 mm plastic scintillators was positively low for the natural radioactivity of γ photons in water, thus verifying the rationality of 1 mm plastic scintillators' absorption detection for β particles.

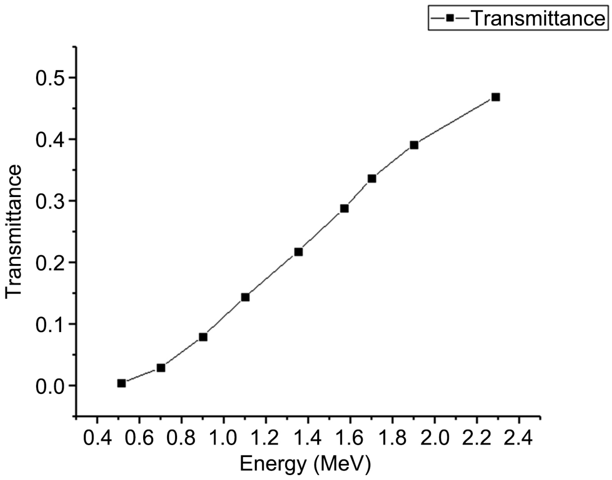

Figure 2. Transmission ratio of β rays through a plastic scintillator of 1 mm.

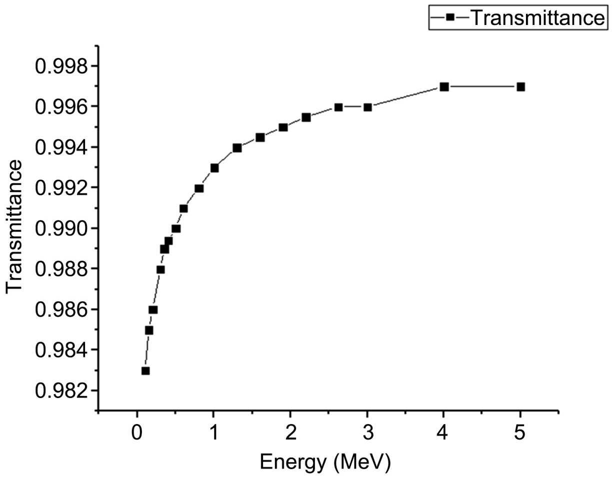

Figure 3. Transmittance ratio of γ rays through a plastic scintillator of 1 mm.

4. Monte Carlo Simulation

This article through the theoretical calculation of ZnS(Ag) and the thickness of the plastic scintillator administered using MCNP to simulate, set the thickness of ZnS(Ag) administered to 30 microns, plastic scintillator thickness to 1 mm, simulated experiment, the particle number is one hundred million β particles energy range of 0 - 3.3 MeV, the total number of 2048, with the F8 to capture card count, and β particles are the data processed and analyzed in ZnS(Ag) and plastic scintillator administered normalized count as shown in Figure 4 and Figure 5.

As shown in Figure 4 and Figure 5, the deposition in the plastic scintillator is higher only in the low energy region, the energy at this point is 1.62×10^{-3} MeV, while the β particle energy in the natural water body is all higher than this energy value, so there will not be too much deposition in the ZnS(Ag) coating, which will not have a great impact on the detection of α particles. For the deposition of

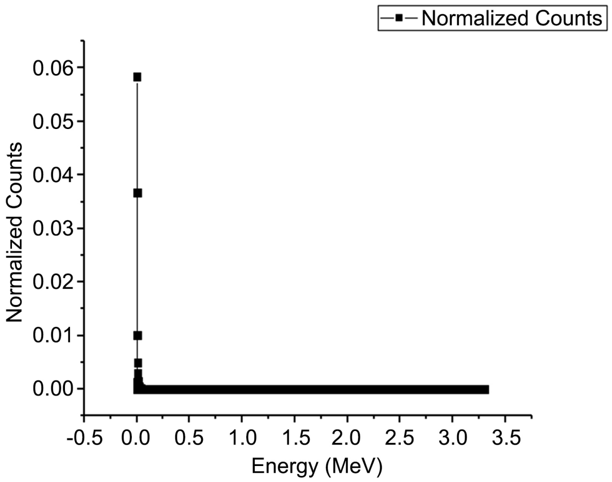

Figure 4. Normalization count of β particles in ZnS(Ag).

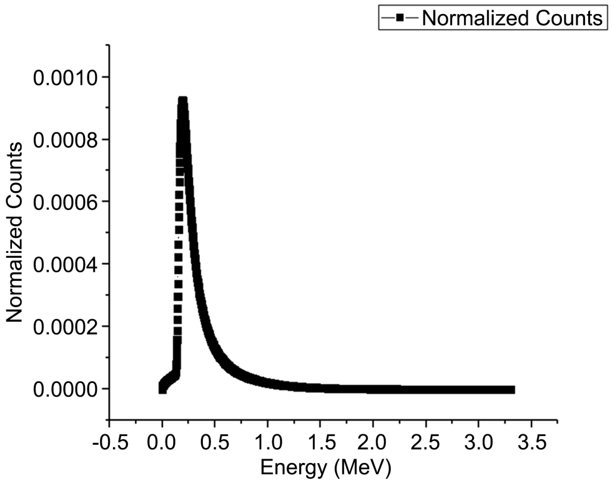

Figure 5. Normalized count of β particles in a plastic scintillator.

β particles in plastic scintillators, the energy range of β particles is 5.96×10^{-2} - 1.25 MeV. In natural water, the energy range of β particles is mostly within this energy range, so it can meet the energy detection of β particles.

5. Conclusion

In this paper, a new design idea is proposed for the online measurement of α and β particles in natural water bodies. Compound detector determined by theoretical calculation and numerical simulation of ZnS(Ag) administered the thickness of the coating in 30 μm, the thickness of the plastic scintillator in 1 mm, can be completed for α and β ray detection, and also can reduce the interference of γ photons, α and β particles in natural water bodies of online measuring complex detector design has a certain reference value.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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