Energy spectra test of glass scintillator

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Hadronic calorimeter (HCAL) is an important part of the calorimeter system in Circular Electron Positron Collider (CEPC). The design of glass scintillator coupled with silicon photomultiplier (SiPM) was proposed by the Institute of High Energy Physics of Chinese Academy of Sciences. How to explore and improve the scintillation performance of the glass is the key of current research. The energy spectra of the glasses under X-ray, γ-ray, proton beam were measured. And the relationship between X-ray luminescence intensity, Gamma light yield (LY) and minimum ionizing particle (MIP) response of the glasses was investigated. The results indicate that Gamma light yield and MIP response can accurately reflect the scintillation properties of the glass scintillator.

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1. Introduction

1.1 GS-HCAL

Scintillators are a mediator used to detect high energy rays and particles and convert them into visible light. Generally, solid scintillator can be divided into crystal, plastics, ceramic and glass. Crystal scintillator has been widely applied in nuclear radiation detection, medical imaging and high energy physics [1]. However, it still has limitations due to the complex preparation process and high cost. In recent years, researchers began to explore other scintillators for nuclear physics applications. The Circular Electron Positron Collider (CEPC) is a large international scientific facility proposed by the Chinese particle physics community. To achieve accurate measurement of Higgs, W and boson properties, CEPC needs to cover a wide range of solid angles, excellent particle identification, accurate measurement of particle energy momentum, and high resolution of the collision vertex [2]. Hadronic calorimeter (HCAL) is an important part of the calorimeter system, which can measure neutral hadrons. Therefore, researchers proposed a sampling calorimeter with a plastic scintillator-tungsten structure in HCAL [3]. But it has low density and poor irradiation resistance. In such background, glass scintillators are attracting attention due to low cost, flexible composition and large volume preparation. As a traditional material, glass has high density, high transparency and stable physical and chemical properties. In 2021, the design of glass scintillator (GS) coupled with silicon photomultiplier (SiPM) was proposed by the Institute of High Energy Physics of Chinese Academy of Sciences [4]. According to preliminary simulations, the glass scintillator is required to have a density of 6 g/cm^3 and a light yield of more than 1000 ph/MeV.

1.2 Glass scintillator

Scintillation crystals have better luminous consistency under different excitation sources. However, glass is characterized by short-range ordered and long-range disordered structure and contains a large number of wrong bonds, which is easy to be caught by deep traps during the process of electron and hole migration, thus greatly reducing the probability of radiation transition and light yield. Hence, how to explore and improve the scintillation performance of the glass is the key of current research. In order to meet the demand for new glass scintillator in high energy physics and nuclear radiation detection, in 2021, the Institute of High Energy Physics, together with other institutions, established the Large Area Glass Scintillator Collaboration (GS Group) to to jointly develop the glass scintillator for HCAL of CEPC. Based on the demand for scintillation glass in the proposed large collider with high energy (density >6 g/cm^3, light yield >1000 ph/MeV, attenuation time <100 ns), GS group develops new glass scintillators, including glass composition and formulation, comprehensive performance studies, large size/volume manufacturing and application technology development. In this work, We tested the energy spectra of the glass scintillators under X-ray, Gamma ray (^{137}Cs radioactive source), proton beam. And the relationship between X-ray luminescence intensity, Gamma light yield (LY) and minimum ionizing particle (MIP) response of the glass scintillators was investigated.

2. Test method of energy spectrum

2.1 Test facility

Fig 1 shows the test facility of energy spectra of glass scintillators under different excitation sources. The samples were wrapped with Teflon film, and one side was coupled with the SiPM (MPPC Hamamatsu, S13360-6050CS) through silicone optical grease (SAINT-GOBAIN, BC-630). The SiPM was driven by a driver circuit Hamamatsu C12332-01. The power supply circuit board was operated by connecting to an external DC power supply with ±5V. The scintillation light signals from SiPM were acquired using a 4-channel, 10-bit, 1 GHz, USB-based Flash Analog-to-Digital Converter (FADC) with the waveform digitizer DT5751. The scintillation light waveform is recorded by DT5751, and then the energy spectrum is obtained by charge integration.
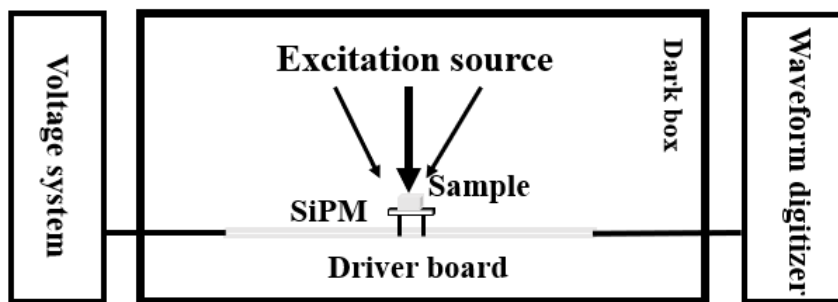

Figure 1: Test facility of energy spectrum

2.2 Multi-photoelectron charge spectrum of SiPM

SiPMs can detect weak light in a wide range of wavelengths, from ultraviolet to near-infrared. The energy spectrum testing system in the laboratory can detect the weak light at the level of single photon, which provides conditions for testing the energy spectrum and full-energy peak of glass scintillators with low light yield. Fig 2 shows the multi-photoelectron charge spectrum of the SiPM (MPPC Hamamatsu, S13360-6050CS). The difference between adjacent peaks represents the number of channels of a photoelectron, and the channel number of a single photon is 110.
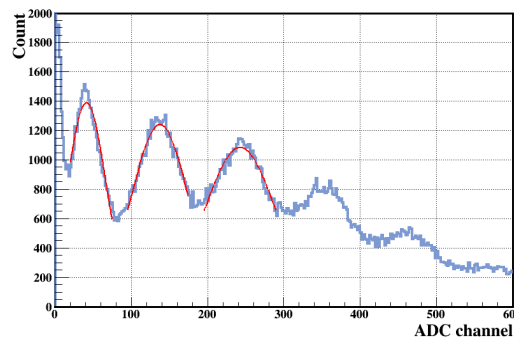

Figure 2: Multi-photoelectron charge spectrum of SiPM

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3. Typical energy spectrum

3.1 X-ray excited luminescence spectra

The Omni-λ 300i spectrophotometer (Zolix, Beijing, CN) with MAGPRO W target X-ray sources (Moxtek, Tianjin, CN) was used to record X-ray excited luminescence (XEL) spectra of the glass scintillators. The X-ray generator was supplied by a bias voltage of 50 kV, and the irradiation dosage was controlled by the tube current. As shown in Fig 3(a), the glass scintillator show broadband emission in the 300-600 nm range, with emission peaks around 400 nm. A shoulder peak can be observed in the spectra near 450 nm. It could be ascribed to the characteristic absorption transitions of Ce^{3+} centers from 5d level to the two ground-state ($^2F_{5/2}, ^2F_{7/2}$) [5]. Through calculation, the XEL peak and integral intensity of GS-1 glass are 22.6% and 14.2% of BGO crystal, respectively.
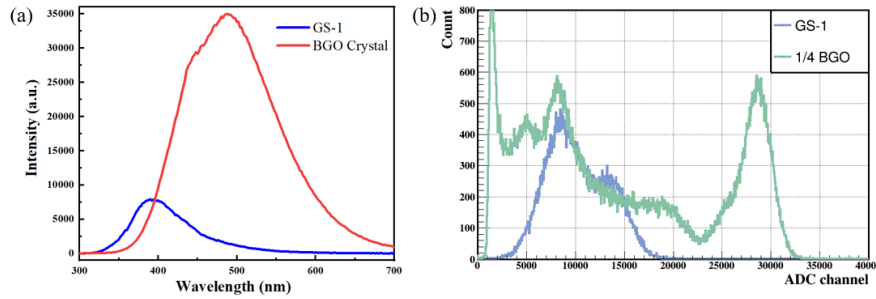

Figure 3: (a) XEL spectra, (b) Gamma energy spectra of the glass and BGO crystal

3.2 Gamma energy spectra

Fig 3(b) shows the energy spectra of the glass and BGO crystal under ^{137}Cs $\gamma - ray$. he light yield (LY) and energy resolution of the glass scintillator are further obtained from the energy spectra. The LY calculation formula of scintillators can be expressed as:

$$LY = \frac{M_1 \times 1000 keV}{S \times \epsilon_{PDE} \times E_1}. \tag{1}$$

where LY is the light yield of the glass scintillator, M_1 is the channel number in the energy spectrum of γ source, S is the single photoelectron channel number of the SiPM, ϵ_{PDE} is determined by the emission spectrum of scintillator and the photo detection efficiency (PDE) of SiPM, E_1 is the energy of γ source. By fitting the full-energy peak of 662 keV, the LY of the glass is 611 ph/MeV with an energy resolution of 34.4%.

The relationship between XEL integral intensity and Gamma light yield of glass scintillator was compared, as shown in Table 1. The XEL intensity and light yield of the glass are not consistent due to re-trapped process during the transport stage [6]. Therefore, only the XEL test of the glass can not correctly reflect its scintillation properties. A complete energy spectrum test of the glasses is necessary.

Table 1: Comparison of XEL, LY of glass and BGO crystal

Label	Relative XEL integral intensity	Relative LY	LY (ph/MeV)
GS-1	0.142	0.086	611
BGO	1	1	7070

4. Beam experiment

Beam experiment is an important means to explore the energy deposition and scintillation characteristics of glass scintillator. The MIP response of an individual detector unit provides the energy scale for the energy reconstruction of HCAL [7]. We obtained the energy spectra of glass scintillators in CERN Proton Synchrotron (primary 24GeV protons). The glasses wrapped with Teflon foil and is coupled with silicone optical grease to a multi-pixel photon counter (SiPM Hamamatsu, S13360-6025CS). Fig 4 shows the MIP response of the glasses. By Landau convolution Gaussian fitting, the most probable value (MPV) of the glasses are 66, 31 photoelectrons, respectively. The MIP response depends on the density and thickness of the scintillator, with F_c defined as MIP/(Density×Thickness). In order to investigate the consistency of MIP response and light yield (LY) of the glasses, the energy spectra under ^{137}Cs γ-ray source were recorded, as shown in Fig 5. The accuracy of test results was compared by calculating LY/F_c. The results indicate that the MIP response of the glasses is consistent with the Gamma light yield. And the MIP response can also accurately reflect the scintillation properties of the glass.
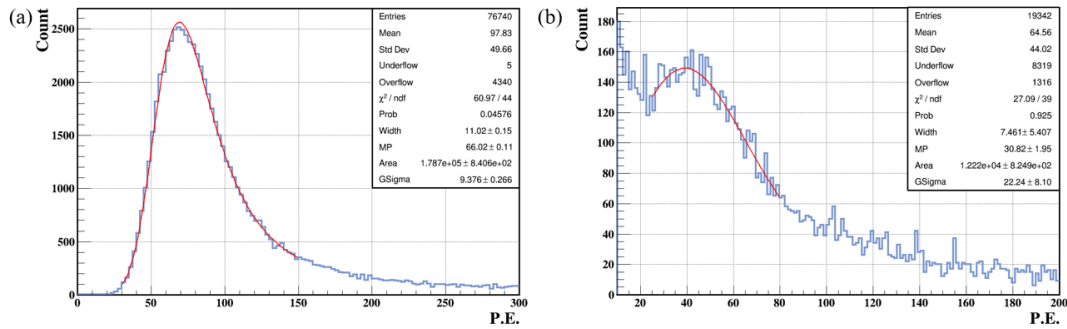
Figure 4: Energy spectra of (a) GS-2, (b) GS-3 under proton beam

Table 2: The MIP, light yield and other relevant parameters of the glasses.

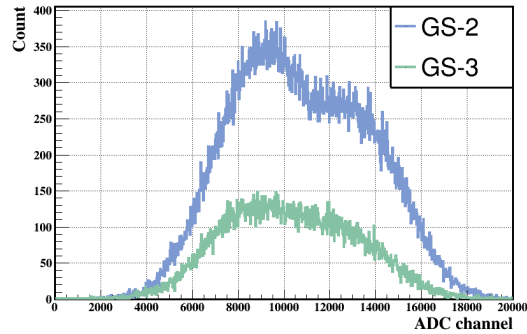| Label	MIP (p.e.)	LY (ph/MeV)	Thickness(mm)	Density (g/cm^3)	F_c	LY/F_c
GS-2	66	617	10.2	5.1	1.27	486
GS-3	31	571	5.3	5.1	1.15	497

Figure 5: Gamma energy spectra of GS-2 and GS-3 glasses

5. Conclusion

In order to meet the demand for new glass scintillator in high-energy physics experiments and nuclear radiation detection. In September 2021, led by the Institute of High Energy Physics of Chinese Academy of Sciences, domestic universities, research institutes and enterprises jointly established a New large-area scintillation Glass Development Cooperation Group (The Large Area Glass Scintillator Collaboration).

The energy spectra of glass scintillators under X-ray, γ-ray and proton beams were tested. And the relationship between XEL intensity, Gamma light yield and MIP response of was explored. Due to the large number of defects in the glass, the XEL intensity and light yield of the glass are not consistent. The hole-electron pair will be re-trapped during the transport stage in scintillation process. The parameters F_c related to density and thickness of the glass are defined. Normalized through density and thickness, the MIP response is consistent with the Gamma light yield of the glasses. Therefore, it is proposed that Gamma light yield and MIP response can accurately reflect the scintillation properties of the glass scintillator.

Acknowledgement

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