Geant4 simulation of plastic scintillators for a prototype SR spectrometer (Postprint)

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Full Text

Geant4 Simulation of Plastic Scintillators for a Prototype SR Spectrometer

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Abstract

The experimental muon source on China Spallation Neutron Source (CSNS) is expected to be a high-intensity (10^5 $^+$/s) surface muon source with a small beam spot of 4-cm diameter. For practical application of this muon source, we are devoting ourselves to developing the first pulsed SR spectrometer in China. In this paper, the performance of plastic scintillators in the SR spectrometer is studied by Monte Carlo simulation. The processes such as positron energy deposition, scintillation photon production, light propagation, and photon-electron conversion are carefully considered. According to the results, an optimal dimension of the plastic scintillator is proposed for our future spectrometer, which has a long-strip shape with a dimension variation range of 50–60 mm length, 5–8 mm height, and 10–12 mm width. Finally, we can build a spectrometer with a count rate up to 10^4 e^+/s using 100–120 forward and backward segmental detectors in total. The simulation could serve as an important guide for spectrometer construction.

Keywords: SR Spectrometer, Plastic scintillator, Monte Carlo simulation, Scintillation photon transmission

1 Introduction

The China Spallation Neutron Source (CSNS) is an accelerator-based facility comprising a proton accelerator, a neutron target station, and multiple neutron scattering spectrometers. An intense neutron source will be produced by a 1.6-GeV proton beam bombarding a high-Z metal target [**?**, **?**]. In Phase I, a 120-kW proton beam, neutron beam intensity of 2.0$×10^{16}$ n/cm^2 · s, and 25-Hz synchronic frequency will be achieved. Besides serving as a neutron source, CSNS can also be used as a potential muon source [**?**].

The Experimental Muon Source (EMuS) [**?**, **?**], which is proposed for Phase I, is expected to deliver a surface muon source with beam intensity of ~10^5 $^+$/s, beam spot of 4-cm diameter, and 1-Hz pulse frequency. Using this new muon source, a spectrometer for SR spectroscopy (Muon Spin Rotation, Relaxation, Resonance, etc.) [**?**, **?**] is essential and currently under development.

Fig. 1 schematically shows a pulsed SR spectrometer. Nearly 100% polarized surface muons are injected into a specimen and decay into positrons asymmetrically distributed in the full 4π solid angle. A muon counter before the SR spectrometer is used to count incoming muons as a start signal, and two sets of segmental detectors located forward and backward relative to the sample are used to detect the positrons as stop signals. The lifetime of muons in materials can be measured by registering the start and stop signals. Finally, we can obtain the positron spatial distribution as time evolves to explore the internal structure and dynamics in condensed matter under various extreme conditions.

Fig. 1. Schematic of the SR detection system. Positrons from muon decay are asymmetrically distributed in space with an angular distribution: $\mathrm{P}(\alpha) = 1$

+ A cos(α).

The type of μSR spectrometer is dependent on the time structure of the muon source: continuous or pulsed [**?**]. Benefiting from the development of detection and superconductor techniques, researchers are developing novel μSR spectrometers with improved performance. Photodiode detectors with small dimensions, high detection efficiency, and low magnetic sensitivity are used to replace traditional PMTs to achieve higher timing resolution of 100 ps [**?**]. Superconductors are used to supply a high external magnetic field up to 5 T for special μSR studies [**?**]. Silicon microstrips serve as position-sensitive detectors for spatial-temporal μSR spectroscopy [**?**]. New data acquisition systems are being developed for large scintillator detector arrays [**?**]. The realms of μSR spectroscopy will be dramatically broadened by these advanced spectrometer techniques.

For our construction, we must utilize many small detectors to detect large numbers of positrons in a short time interval of around 2.2 μs. The sizes of the scintillator detectors play a significant role in structural design, optical coupling, transmission, and signal processing. Unfortunately, the performance of the positron detectors cannot be tested using a variable-energy positron beam of 0–53 MeV, so one can only determine the scintillator parameters based on experience. Therefore, we performed Monte Carlo simulations to study the plastic scintillator in the μSR detector system; other simulations for μSR spectrometer construction can be found in Refs. [**?**, **?**].

In Section 2, the simulation configuration, parameters, and approaches are briefly introduced. Many physical quantities are studied, such as the energy deposition and muon energy loss rate (K) in a scintillator, the transition probability (P) of positron energy to scintillation photons, light yield (R), and the light transmission efficiency (T) in various media. The simulation results are analyzed and discussed in Section 4. Finally, a preliminary proposal for our future spectrometer construction is given based on our simulation.

2 Simulation, Configuration and Methods

The physical process to be simulated is as follows: high-intensity surface muons up to 10^5 μ^+/s are injected into a specimen, stopped, and decay into positrons; the positrons are detected by transporting and collecting the scintillation photons produced by the ionization energy loss in scintillators. In this process, the interactions among particles and electromagnetic materials and optical processes can be simulated by a Monte Carlo code–Geant4 [**?**, **?**]. This tool allows us flexible and modular simulation to set many conditions, such as the detector dimensions, the reflector configuration used for scintillator wrapping, the properties of optical media with optical coupling, and the realistic scenario of PMT response.

Fig. 2(a) shows a single channel for positron detection by a plastic scintillator in the μSR spectrometer system. Simulation was carried out using long-strip EJ-200 plastic scintillators with dimensions of 30–100 mm length, 5–15 mm height, and 5-15 mm width. The main characteristics of the scintillator are summarized in Table 1 .

Length (L) and width (W) determine the count rate of the single-channel detector or the integral spectrometer. Meanwhile, light transmission efficiency and positron energy deposition are evidently dependent on length (L) and height (H). In our simulation, the photon exit surface of the scintillator (H×W) is connected with a light guide end of 5 mm$×$5 mm using silicone optical grease with refractive index 1.5, while the other surfaces are covered with a Teflon reflective coating. A 1-meter-long clear fiber BCF-98 serves as a light guide to connect the scintillator and transport the scintillation light to a PMT (ET 9813B) (Table 1b). Detection and measurement can thus be free from the high magnetic field of several thousand Gauss in the central area of the spectrometer. This clear light guide, which has double claddings of 0.5 mm thick acrylic inner and 0.1 mm thick fluor-acrylic outer, is reported in Table 1(c).

The maximum incidence angle of the total-reflection light in the fiber, defined as ϕ{max} *with respect to the long axis of the fiber, is given by:*

$$\sin\phi_{\max} = \frac{\sqrt{n_1^2 - n_3^2}}{n_0}$$

where n_1 and n_3 are the refractive indices of the core material and the outer cladding of the fiber, respectively, and n_0 is the refractive index of the silicon grease coupled with the fiber ends. Using the parameter values, ϕ{max} is calculated to be around 30 degrees. Therefore, a fraction of photons exiting the scintillator will inevitably be lost at the front end of the light guide.

The last part of our simulation models the photon-electron conversion by realistically modeling the PMT cathode, including a 5 mm thick, 51 mm diameter quartz window connected with the exit end of the light guide and a blue-green sensitive bialkali photocathode.

Fig. 2. (a) Sketch illustrating the principle used for positron detection by plastic scintillator. Positrons from muon decay inject into the scintillator strip at an incident angle with respect to the normal of the incident surface. (b) 3D view of segmental detectors in SR spectrometer.

To estimate the positron count rate of a single detector or the spectrometer, we studied a traditional spectrometer with two symmetrical detector segmentations forward and backward (Fig. 2b). The inner end surface (H×W) of either segmental detector ring is 7.5 cm away from the sample center, and the detector unit is 10 cm from the ring center to provide moderate space for a compromise between sufficient sample chamber space and adequate detection solid angle.

The deposited energy is calculated by subtracting the exit energy from the incoming energy. The scintillators in this simulation have a fixed length of 40 mm and width of 10 mm, but variable height of 5-16 mm. Fig. 3(a) shows the deposited energy as a function of positron incident energy of 0-53 MeV for different scintillator heights. Fig. 3(b) shows the energy loss ratio as a function of positron incident energy for variable scintillator heights. An empirical equation for energy loss ratio (K) depending on incident energy (E) and penetration height (H) can be obtained.

3 Results

Firstly, the positron deposited energy in scintillators with variable dimensions was studied by perpendicularly injecting positrons into the down surface and counting the exit positrons from the upper surface. The deposited energy can be calculated by:

$$K(E,H) = (0.12e^{-E/6.3} + 0.017) + (0.084e^{-E/55} + 0.0072)H \tag{1}$$

where E is in the range of 5 to 53 MeV and H is the penetration distance (mm). The constant coefficients for Eq. (1) are calculated by single-exponential curve fitting (^{2}/DoF 0) based on the data in Fig. 3(b) and linear fitting ($R^2 > 0.98$).

Fig. 3. (a) Deposited energy as a function of positron incident energy for nine different scintillator heights; (b) Energy loss ratio as a function of positron incident energy for variable scintillator height.

Figure 4 [Figure 4: see original paper] shows the light yield of positrons in the scintillator calculated with the same sizes as the previous deposited energy simulation at variable heights of 5-16 mm. The vertical axis represents the total light yield of a parameterized scintillator as a function of positron energy of 0-53 MeV. The filled dots (a, b, c, and d) indicate the maximum light yield at certain energies for different scintillator heights. For comparison, dot O marks the light yield of 0.511 MeV γ-rays in the scintillator. As mentioned in Section 2, the scintillation photons are transported far from the sample room via a long light guide, avoiding high magnetic field influence. Consequently, considerable light loss dependent on scintillator size and light guide is expected at the beginning of the light guide.

Fig. 4. Scintillation photon yield for variable scintillator under different incident energy. The red filled dots a, b, c, and d indicate the approximate maximum photon production for the variable scintillator heights. Dot "O" means the photon production for the 0.511-MeV gamma rays.

For example, an 8-mm-width plastic scintillator used as a detector unit means 78\$×\$2 segmentation counters can be integrated in our spectrometer. Other width sizes are detailed in the inset. Additionally, the scintillator length varies from 30 mm to 70 mm.

In our case, the loss is up to 40% when setting an exit scintillator surface of 5 mm\$$\times 10mm(H\times W)andanentrylightguidesurfaceof5mm\times$\$5 mm. For realistic studies, positrons are injected into scintillators at a variable incidence angle ( ) (Fig. 2a). On the other hand, the length of the scintillator strip determines the range in our simulation. For example, a 50-mm-long scintillator strip means that range of 38° to 50° was calculated according to the spectrometer configuration.

Fig. 5 shows the photoelectron count as a function of incident angle for six different lengths. The solid lines are linear fits for these data.

Fig. 6 shows the Minimum Detection Time per Event (MDTE) for different dimensions of scintillators. The dashed box indicates that parameter options in this area meet the requirements of our optimal design.

4 Discussion

The expected pulsed width of the surface muon beam at EMuS is about 100 ns, smaller than the 2.2- s muon lifetime. We must detect the majority of positrons from muon decay within 2.2 s after the muon beam reaches the specimen. When defining the Minimum Detection Time per Event (MDTE), the detection time for a single event in a detector unit should not be less than the ratio of one 2.2- s muon lifetime to the total counts of positrons hitting a single scintillator strip. A small MDTE is important to avoid data pile-up. Fig. 6 shows the MDTE for different lengths and widths of scintillators in simulation with an intense surface muon beam of 10^5 $^{+}$/s. Selecting crystals with different widths (8, 10, 12, 20 mm) represents detector rings with different segmental counter configurations.

For a given scintillator height, we find that deposited energy increases with positron incident energy (Fig. 3a), whereas the energy loss ratio K(E) shows an exponential reduction (Fig. 3b). However, when injecting a positron of given energy, the longer the path the positron experiences (H), the more energy is deposited in the scintillator, and the function K(H) approximately shows linear increase.

Additionally, there is no linear relation between light yield and incident energy (Fig. 4). For scintillator heights of 5 mm to 16 mm, we define positrons with energy less than 5 MeV as Low Energy Positrons (LEP). LEP can be completely stopped in the scintillator, resulting in light yield proportional to incident energy. Further, the stopped positrons will annihilate with electrons, yielding two 0.511 MeV gamma rays. Illumination of the scintillator by these gamma rays will add to the light yield in our calculation. The filled dots (a, b, c, and d in Fig. 4) provide evidence that the 0.511 MeV gamma rays do produce many additional photons. However, for positron energy larger than 5 MeV (Medium Energy Positrons, MEP), the light yield does not increase linearly with incident energy. This is mainly due to the limited scintillation light yield in a fixed-length scintillator for Minimum Ionizing Particles (MIP). Consequently, its light yield R in a given scintillator is only dependent on the height size (H mm):

$$R(H) = -442 + 1880H$$

Finally, the effective efficiency of the energy-light conversion can be obtained by

Eq. (2):

$$\eta = \frac{-442 + 1880H}{E \times [(0.12e^{-E/6.3} + 0.017) + (0.084e^{-E/55} + 0.0072)H]}$$

where E is in the range of 5 to 53 MeV.

It is concluded that the decreasing energy loss ratio and conversion efficiency, which are opposite to the increasing deposited energy, ensure output electronic signals with similar amplitudes for different positron incidence energies. With this result, we can easily distinguish MEP from background particles in detection and achieve positron detection across nearly the full energy spectrum without discrimination for the energy range of 5 to 53 MeV. To avoid undesired LEP detection, a thin aluminum layer is usually placed before the scintillator [**?**].

According to the light yield in scintillators with 5 mm height, the light yield count is large enough (up to 10^4) to distinguish the background from 0.511-MeV gamma rays (for comparison see dot O in Fig. 4). Considering scintillator-guide coupling and light guide cost, we selected the 5-mm height scintillator for our simulation and future experiments.

The distance (D) between the positron incident position and the light-exit surface of the scintillator significantly determines transmission efficiency. An optimal length of the scintillator strip must be found for our spectrometer design. Generally, there is a linear relation between photon loss in the strip and D. Especially for strips longer than 60 mm, the R^2 values are close to 1 (Fig. 5), meaning that photon loss in the scintillator is well correlated with D. The large length of the scintillator strip is the main reason for photon loss.

For an 80-mm length scintillator, the photon collection efficiency for positrons with = 38° (positrons hitting the right end of scintillator in Fig. 2a) is only ~60% compared to = 56° (light-exit end). In this case, the final electronic signal amplitudes will be so evidently different that discrimination threshold setting becomes difficult. However, for lengths of 30 mm and 40 mm, photon collections for different incident angles are not markedly different but rather fluctuant. There is no clear regularity for photon counts at different incident angles. The very small R^2 (< 0.2) indicates a slight relation between length and photon loss.

Consequently, scintillator strips with lengths of 30–60 mm are suitable for controlling signal differences to less than 20%. In this case, we can obtain an average photoelectron count up to 500 electrons per event, resulting in a voltage output of ~1 V after photoelectron multiplication by PMT (gain 10^6, load resistance 50 Ω). However, a determinate-length scintillator must be associated with the detection rate, which is strongly dependent on length and width.

From Fig. 6, selecting a scintillator strip with larger width and length requires a higher detection rate for a single detection channel or the integral spectrometer. The detection time per event can be achieved at a low value of about 20–30 ns for traditional detection equipment, including the fall time in the scintillator, transmission time, rising time in the PMT, and the pulse width necessary for the electronic system in total.

With comprehensive consideration, a scintillator with 50-60 mm length and 10-12 mm width is optimal for positron detection in our SR spectrometer design (the black dashed box in Fig. 6 shows this optimal result). Finally, we can obtain desired performance for our future spectrometer based on the design in this paper: 100-120 detection channels can be sufficiently segmented on the forward and backward detector rings, achieving detection rates of 70-90 e^+/s and ~1.0$×10ˆ{4}$ e^+/s for a single detection unit and the whole spectrometer, respectively. These performances meet the requirements of SR spectroscopy.

5 Conclusion

We have used Geant4 to simulate electromagnetic processes and optical processes in muon lifetime detection and investigated the suitable setup and expected performance of the SR spectrometer at CSNS EMuS. The significant parameters such as deposited energy, light yield, energy-light conversion efficiency, and transport efficiency were calculated and studied, demonstrating that scintillator dimensions play an important role in SR spectrometer construction. A plastic scintillator strip with 50-60 mm length, 10-12 mm width, and 5 mm height is verified as an optimal positron detector for our SR spectrometer. The high light yield and light transmission efficiency in this scintillator meet the requirements for signal discrimination and SR spectroscopy measurement. Currently, a SR spectrometer with 100-120 segmental detection channels is under design and construction at EMuS. Experimental studies of plastic scintillators, a multi-channel detection system, and the data acquisition (DAQ) system are in progress.

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