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Measurement of positron annihilation lifetimes for positron burst by multi-detector array

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ABSTRACT

It is currently impossible to exploit the timing information in a gamma-ray pulse generated within nanoseconds when a high-intensity positron burst annihilation event occurs in a target using conventional single-detector methods. A state-of-the-art solution to the problem is proposed in this paper. In this approach, a multi-detector array composed of many independent detection cells mounted spherically around the target is designed to detect the time distribution of the annihilated gamma rays generated following, in particular, a positron burst emitting huge amounts of positrons in a short pulse duration, even less than a few nano- or picoseconds.

1. Introduction

It is possible to create a high-intensity positron burst with a temporal width of a few sub-nanoseconds or even picoseconds thanks to the technical development of positron trapping [1] and a petawatt-level femtosecond laser-induced positron pulse beam [2]. Such high-brightness positron pulses have become an important direction of development in positron beam technology, greatly promoting the development of basic research in atomic physics such as positron elastic scattering, electron excitation, ionization, and positronium formation.

In these cases, huge numbers of gamma photons are produced in hundreds of ps or a few ns after positron burst annihilation. When the annihilation lifetimes of the positrons in a burst can be obtained, the positron beam technique can be used to study dynamically changing processes at nanosecond time scale with regard to electronic structure and defect configurations in materials, for example irradiation effects [3], laser-induced atomic transitions [4], annealing processes [5], and electron migration in semiconductor materials [6]. However, conventional time-measurement nuclear detection technology cannot pick out time information for each photon of the γ-ray burst arriving in such a short time.

A method called multi-detector measurement is proposed here to deal with this problem. In this method, a multi-detector array composed of enough independent detector cells is designed to separate the annihilated photons by spatial solid angle to ensure that every detector cell can give a stop signal for a positron lifetime. Hence, the method can be used to determine the lifetimes in a positron burst. In principle, a spectrum of positron annihilation lifetimes can be obtained from only one burst if the number of detector cells and the number of positrons in the burst are large enough.

As main performance parameters for a positron annihilation lifetime spectrum (PALS), the time resolution and count rate of this method should be taken into account. Besides the time response of the detectors, the time width of the primary positron pulse also defines the timing resolution of the technique. Because positrons are distributed within the pulse time width, the arrival time of positrons impinging upon a target is not synchronous, which affects γ photon generation time. When a multi-detector array records positron burst annihilation information, the total number of photon timing signals obtained definitely depends on detection efficiency and the number of detector cells. Fundamentally unlike the γ-signal counts per second obtained from conventional techniques, the count rate of this method is defined as γ-signal counts per pulse. This paper reports the results of efforts by the authors to research the influence of factors on various two parameters. Briefly, for optimal timing resolution, a PALS measurement should have fast-time-response detector cells and ultrashort-time positron bursts, whereas for high count rate, a multi-detector array should have numerous detector cells that are sensitive to annihilation gamma photons.

2. Principle of the multi-detector method

Based on the random distribution of the annihilation gamma photons in 4π space (the angle correlation effect is neglected) [7], the main

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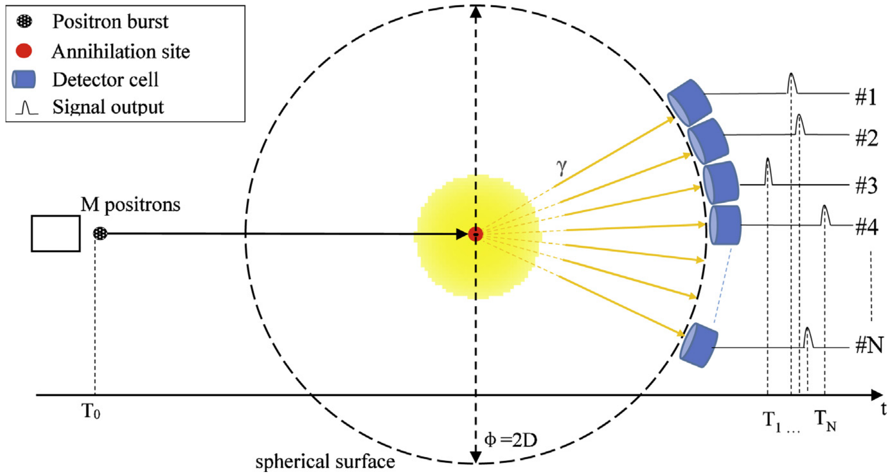

Fig. 1. Schematic diagram of the multi-detector method for measuring the annihilation lifetimes for a burst of M positrons with N detector cells.

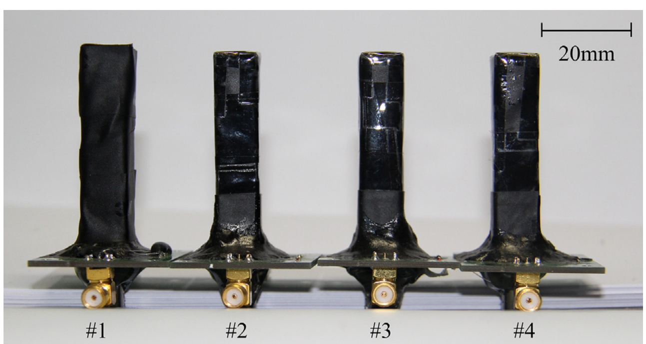

Fig. 2. Four SiPM detector cells with 10×10 mm effective detection area. Unlike the high working voltage (a few thousand volts) of photomultiplier tubes, the normal operating voltage of the SiPM is about 57 V. The SiPM detector has only one output, which matches the 50 ohm resistance.

principle of this method is that with a high-time-resolution detector array composed of enough detector cells (the number is N), a burst of gamma rays extends from the annihilation "point" to a sufficiently large spherical surface on which detector cells are arranged for measurement. As shown in Fig. 1, a positron burst containing M positrons injects into a certain depth range of the sample and annihilates to γ rays almost simultaneously (thermalization can be considered negligible compared to the positron annihilation lifetime). The positron annihilation lifetime is calculated as $(T_i - T_0)$, where T_0 is the starting time of a positron burst obtained by synchronizing a signal from a beam buncher or laser and T_i is the stopping time of the annihilation photon detected by $\#i$ detector cell ($i = 1$ to N). The statistics of all the values T_i represent the annihilation lifetime spectrum of the positron burst.

There are three factors, Ω, n, and η, that affect the detector cell efficiency p. More specifically, Ω is the ratio of the geometrical solid angle of a detector cell to 4π, n is the number of photons that reach the detector cell surface S, and η is the detection efficiency for the annihilation gamma ray of a cell. Ω decreases with increasing distance (D) when the area S of the cell is fixed and is represented as Eq. (1).

$$\Omega = S/4\pi D^2 \tag{1}$$

For a positron burst beam of intensity M, the average number of incident photons is:

$$n = 2M \cdot \Omega \tag{2}$$

For a gamma photon, the probability of an event occurrence is equal to the single-γ detection efficiency η, whereas the probability of no event occurrence is $(1-\eta)$. For n photons, each photon is independent of the others. According to the occurrence probability of independent events in probability theory, the detection efficiency p of a detector cell is as follows:

$$p = 1 - (1-\eta)^n \tag{3}$$

For an array with N detector cells in which each detector cell works independently, the detection efficiency of the multi-detector array satisfies the Bernoulli probability model as shown in Eq. (4), where $q = 1 - p$. The equation represents the probability of k cells having signal outputs simultaneously.

$$b(k; N, p) = C_N^k p^k q^{N-k} \tag{4}$$

Actually, each detector cell has its own detection efficiency (p_i), and the detection efficiency of a detection array is P:

$$P = 1 - \prod_{i=1}^{N} \left(1 - p_i\right) \tag{5}$$

According to Eq. (4), the probability K of all cells having signal outputs is:

$$K = \prod_{i=1}^{N} p_i \tag{6}$$

If p_i is replaced by Eq. (3), K can be expressed as $K = \left[1 - (1-\eta)^n\right]^N$. Hence, K is affected by N, n, and η, or in other words, the detection efficiency of a detection array depends on these three factors.

3. Experimental

To determine the actual detection efficiency relationship, the experiments described below were carried out.

The experiments were performed using a RGM-1/APBS Trap positron source system manufactured by First Point Scientific, USA. In this case, a continuous slow positron beam was obtained with an intensity of $\sim 10^6$ e^+/s, and a high-density positron burst around 10^5 e^+/pulse was generated in a 2 ns-wide pulse into a pure Fe target.

In the initial experimental setup, four detector cells (Fig. 2) equipped with plastic scintillators of 10 × 10 × 50 mm were optically coupled to a Hamamatsu S13360-3050PE silicon photomultiplier (SiPM) with an effective photosensitive area of 3×3 mm, individually working with fast response time and high single-γ sensitivity.

The beam intensity was measured in real time using a NaI(Ta) detector with known detection efficiency (84% for a 0.511 MeV gamma ray at a distance of 1 m).