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Test of 2 mm-Thick TOF Scintillation Counters

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Abstract

The performance of 2 mm-thick TOF counters was examined under various combinations of different scintillator sizes, light-guides, and photomultipliers (PMTs) with the use of a 2-GeV/c beam. The obtained time resolution (σ) was 90 ps for a 50 mm^w×150 mm^l counter with directly coupled 2 in. diameter PMTs and 140 ps for a 150 mm^w×250 mm^l counter coupled through twisted light-guides to the PMTs. A 40 mm-thick 150 mm^w×1200 mm^l counter was also tested, and 60 ps was obtained.

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1. Introduction

A time-of-flight (TOF) system will be employed to identify positrons in our proposed experiment: a precise study of the $K^+ \rightarrow \pi^0 e^+ \nu$ decay using stopped K^+ [1]. It demands $\sigma=150$ ps of overall time resolution in order to separate the positrons from the most energetic muons of $\mu^+ \nu$ decay by more than 5σ with a flight path-length of 2.6 m. Since a stopped K^+ decays randomly in time, the TOF start signal should be produced by the positron itself. Because of the low momentum of the objective positron (30-240 MeV/c), this start counter must be as thin as possible in order to significantly suppress the positron's interaction rates of annihilation, bremsstrahlung and multiple-scattering as well as its energy-loss amount, but must be thick enough to provide the required time resolution. It is accordingly optimized to be 2 mm thick. A stop counter, on the other hand, is designed to be 40 mm thick, since no restriction exists on its thickness.

The performance of TOF counter has been extensively studied, and as a result it is found that time resolution is predominantly determined by photon statistics. The so-called Atwood formula [2] adequately gives the achieved resolution (σ) as

$$\sigma \propto \sqrt{L/N_e}, \quad (1)$$

where N_e is the average number of photo-electrons and L is the counter length. Most measurements [3-6] were performed for a few to several cm-thick scintillation counters, so that a quite large number of photo-electrons could be produced to give a time resolution of 100 ps or better, even with one meter or longer scintillators. Measurements using a thin scintillator [7,8] are, however, scarce, and no report has been found concerning the TOF performance of a few mm-thick counter for a relativistic particle to the author's knowledge. We therefore carried out a test measurement, and report here its result for two different 2 mm-thick scintillation counters having different areas and with various combinations of light-guides and photo-multipliers (PMs).

2. Design of the test counter

Two 2 mm-thick scintillators having different areas were chosen for the start counter. One (denoted as L-type hereafter) was $150 \text{ mm}^w \times 250 \text{ mm}^l$, which covered the necessary spacial area in the experiment; the other (S-type) was one fifth the size of the L-type, $50 \text{ mm}^w \times 150 \text{ mm}^l$. The stop counter (ST) was 40 mm-thick and had a size of $150 \text{ mm}^w \times 1200 \text{ mm}^l$. A plastic scintillator (Bicron Co. BC-408) was used for all of the counters.

Seven kinds of start counters were prepared, as illustrated in Fig.1 and listed in Table 1. PMs were coupled at both ends of the scintillators. Three types of PMs (Hamamatsu R4868 (3/8 in. diameter), H5010 (3/4 in.), and H1949 (2 in.)) were chosen. They have good time characteristics, such as the rise time, transit time, and transit time spread of 1.1 ns, 11 ns, and 0.7 ns for R4868, respectively; 1.3 ns, 14 ns, and 0.36 ns for H5010; 1.3 ns, 28 ns, and 0.55 ns for H1949. The light-guides were made of UV-transparent lucite and were designed to match the full surface of the PM photocathode. Two sets of the counters (S1 and S2 and L1 and L2) were used to compare the effects of the different characteristics of the PMs. S3 was directly mounted on H1949, since it had a sufficiently large photocathode diameter to cover the whole side area of the scintillator. In order to study the effect of different light-guides, L2 and L3 were assembled with fishtail (FT) and twisted (TW) light-guides, respectively, but both viewed by H1949. Since four-side readout was supposed to collect light with higher efficiency than the two-side readout, L4 was prepared so as to compare with L2.

All of the counters were wrapped by aluminum foil so as to collect as much light as possible, especially regarding the start counters, although no noticeable wrapping effect in the time properties was reported [7].

3. Beam test

A test experiment with the set-up shown in Fig.2 took place in the T1 beam line at the KEK 12-GeV PS. A negative unseparated beam of 2 GeV/c, mostly being

pion, was defined by three trigger counters (DF1(6 mm^w×15 mm^l×15 mm^l), DF2(10 mm^w×15 mm^l×6 mm^l), and DF3(6 mm^w×15 mm^l×20 mm^l)). One PM was coupled to the end of each scintillator along the length axis and set vertically. A TDC start signal was generated by DF2 in coincidence with DF1 and DF3. The coincidence rate varied from 40 to 100 Hz, depending on the accelerator condition. S- and L-type test counters were placed between DF2 and DF3, and ST downstream of DF3.

Anode output signals from all PMs were sent via 22 m-long 5D2V cables to a counting room. The test-counter signal was fanned out by a resistive divider into two. One was sent through a 100 ns delay cable to a discriminator, whose output was fed as a stop signal to a CAMAC-TDC (28 ps/count) for a time measurement. The other was to a CAMAC-ADC (0.25 pC/count) for pulse-height recording through a set comprising an attenuator, an amplifier (gain of ×10) and a 100 ns delay cable. An additional amplifier was put in before the discriminator of both S2 and L1 in order to supplement their small pulse-heights. The anode output of DF2 was treated the same as those of the test counters. Table 1 also lists typical high-voltage (HV) values applied to individual PMs. The discriminator threshold was set at 1/20 of the signal pulse-height; it was 20-70 mV, depending on the counters.

4. Result

4.1 Method of analysis

Prior to the following analysis, events with a low DF2 pulse-height are removed.

The time-walk is evaluated based on the relation between the measured time and pulse-height distributions with the following conventional form [3], and the measured time are corrected by an amount of the second term,

$$t = \bar{t} + K\left(\frac{1}{\sqrt{\bar{q}}} - \frac{1}{\sqrt{q}}\right), \quad (2)$$

where t and q are the recorded TDC and ADC counts, respectively, $\bar{t}$ and K are the free parameters determined by the least-square fit, and $\bar{q}$ is a certain reference value. Fig.3 shows, as an example, scatter plots of time vs. pulse-height and their projected time distributions of the left side PM of L3 with and without the time

walk correction. K and $\bar{q}$ for each PM are evaluated at the center of the counter; the thus-obtained values are then applied in order to analyse data taken at different hit positions.

Taking the mean time ($t_+(i)$) of the time-walk corrected TDC counts of the left and right PMs ($t_L(i)$ and $t_R(i)$) of counter i ,

$$t_+(i) = [t_L(i) + t_R(i)]/2, \quad (3)$$

the following combinatory τ 's among three counters are composed as

$$\tau(i-j) = t_+(i) - t_+(j), \quad \tau(j-k) = t_+(j) - t_+(k), \quad \tau(k-i) = t_+(k) - t_+(i). \quad (4)$$

Their root-mean-squared's ($\sigma_\tau(i-j)$'s) of the lefthand side of the above equations are then expressed in terms of the intrinsic resolutions ($\sigma(i)$, $\sigma(j)$ and $\sigma(k)$) of the individual i , j and k counters, respectively, as

$$\sigma_\tau^2(i-j) = \sigma^2(i) + \sigma^2(j), \quad \sigma_\tau^2(j-k) = \sigma^2(j) + \sigma^2(k), \quad \sigma_\tau^2(k-i) = \sigma^2(k) + \sigma^2(i), \quad (5)$$

and are obtained from the data. Accordingly, the σ 's can be deduced by solving these equations. The effect of the start-time fluctuation (σ_s) is essentially cancelled out in this manner. Fig.4 shows a t_L -vs.- t_R scatter plot and t_- and t_+ distributions for S3, where $t_-(i)$ is half of the time difference, defined as $[t_L(i) - t_R(i)]/2$.

σ_s can also be obtained by solving the above equations (eqs.(5)) with $i=0$ (DF2 counter assigned) as $\sigma_s=\sigma(0)$. $\sigma_s \simeq 78$ ps is found; while rotating DF2 by 90° around its length axis $\sigma_s \simeq 59$ ps is attained. Subtraction of the beam-spread effect by supposing a light propagation velocity of 15 cm/ns (see subsection 4.5) results in a time resolution of DF2 of 72 ps and 52 ps, respectively.

In order to estimate N_e (as below), the ratio (R) of the pulse-height difference between the left and right PMs to their sum is formed, and its rms (σ_R) is calculated from data taken at the center of the counter [9],

$$R \equiv \frac{h_L - h_R}{h_L + h_R}, \quad (6)$$

$$\sigma_R = \frac{1}{\sqrt{N_e}}, \quad (7)$$

where h_L and h_R are the pulse-heights of the left and right PMs, respectively, whose distributions are normalized so as to have the same gain with each other. N_e is resultant an average of sum of the photo-electrons measured by the both side PMs. Fig.5 shows, as an example, the R distributions of S3 and ST. They clearly exhibit Gaussian shapes in spite of the Landau distributing deposited energy in the scintillator. The beam-spread effect on N_e can be ignored in our case.

4.2 Time resolution at the center of the counter

The $\tau(i-j)$ distributions are shown in Fig.6. The resulting σ and N_e for all of the counters are listed in Table 2.

For a 40 mm-thick counter, $\sigma(ST)$ is 57 ps and $N_e(ST)$ is 1700.

For 2 mm-thick scintillators, S3 with directly mounted PMs provides a much better resolution of 89 ps than do two other S-type counters of $\sigma(S1)=379$ ps and $\sigma(S2)=200$ ps. It should be attributed to the highly efficient light collection of S3 compared to others, as shown in Table 2. While the fact that $\sigma(S3)=\sigma(S2)/2.2$ is well understood in terms of eq.(1) and the evaluated relation of $4.2 \times N_e(S2)=N_e(S3)$, the achieved $\sigma(S1)$ is much worse than the ~ 270 ps expected from $N_e(S1)$ along with the above argument. It could be inferred that the portion of efficient fast photons for a time measurement decreases with the PM size, and that half of the light collected by S1 might be slow photons.

The transmission efficiency (η_T) of scintillation light to both ends of the S-type scintillator is evaluated from $N_e(S3)$ to be $\eta_T \simeq 24\%$, as

$$N_e = N_\gamma \cdot \eta_T \cdot \eta_C \cdot \eta_{QE}, \quad (8)$$

where N_γ is the number of produced scintillation-light yields calculated based on the energy-loss of $dE/dX|_{min}=2$ MeV/cm and one-photon yield by a 100 eV energy deposition. η_{QE} is the quantum efficiency of the PMs, which is 23, 27, and 26% for R4868, H5010, and H1949, respectively. η_C is the light-collection efficiency of the light-guide, and is approximately unity for S3. Since η_T is the same among the S-type counters, η_C of the FT light-guides is obtained with eq.(8) as $\simeq 23\%$ and $\simeq 14\%$, respectively, for S2 and S1.

L3 with TW light-guides yields $\sigma=140$ ps, while L1 and L2 with FT light-guides yield $\sigma=440$ ps and 216 ps, respectively. Although H1949 used for L2 and L3 has slightly inferior time properties than does H5010 for L1, the 7 times larger photocathode area of the former than the latter could collect sufficient light to successfully overcome these different PM characteristics. The resulting relation, $\sigma(L2)=\sigma(L1)/2.0$, is again well explained by the obtained relation of $3.8 \times N_e(L1)=N_e(L2)$ through eq.(1). The 2.7-times larger diameter of H1949 collects 3.8-times as much light as does H5010. It is noticed from a comparison between L2 and L3 that the TW light-guides provide 1.6-times more light than do the FT light-guides. $N_e(L3) \simeq 125$ is, however, obviously lower than $\simeq 180$, which is required to realize its attained resolution in terms of eq.(1) along with the data of L1 and L2. This fact demonstrates the essential value of isochronous light collection of TW light-guides. Tanimori et al. [5] found an $\sim 7\%$ improvement in σ by using TW light-guides for a 2 cm-thick scintillator, but not for a 3 cm-thick one. The improvement in σ with the TW light-guide thus seems to become more significant as the scintillator thickness becomes thinner.

$\sigma(L4)=213$ ps is obtained in terms of $\sigma^{-2}(L4) = \sigma_{UD}^{-2} + \sigma_{LR}^{-2}$, where σ_{UD} and σ_{LR} are the resolutions comprising up and down PMs as well as left and right PMs of L4, respectively. The four-side readout by L4 does not improve anything on the resolution compared with the two-side readout by L2. Although the former increases the overall N_e to 1.6-times more compared to the latter, the realized resolutions of σ_{UD} and σ_{LR} , and thus $\sigma(L4)$, are worse by 25% than those expected from $\sigma(L2)$ and $N_e(L2)$ through eq.(1). The reason for this is not clear at the moment.

The overall photo-electron conversion efficiency ($\eta_{all} \equiv N_e/N_\gamma$) is given in Table 2. S3 and L3 exhibit conspicuous figures among them.

4.3 Light-yield dependence of the time resolution

The effective scintillator thickness to the beam was varied by tilting the start counters, and the resolution was studied at the center of the counters. The tilting angle was 45° and 60° , corresponding to an effective thickness (t_{eff}) of 2.8 mm and 4 mm, respectively. Fig.7 shows σ vs. $t_{eff}^{-1/2}$, where the lines are the fit with $\sigma \propto t_{eff}^{-1/2}$.

for each counter. The N_e 's for three different counter thicknesses obviously show a proportional relation with t_{eff} . For instance, $N_e(L3) \simeq 125, 181$ and 247 at tilting angles of 0° , 45° and 60° , respectively. Resultantly, eq.(1) is found to be valid for individual counters.

4.4 Position dependence of the time resolution and pulse-height

The time resolution has been studied as a function of the hit position (x) relative to the center of the counter along the scintillator (see Fig.8). It is found to be nearly independent of the hit position for all the test counters.

The position dependence of the pulse-height has been found to comprise two exponential components for both L3 (see Fig.9) and S3: $A_S \cdot \exp(-l/\lambda_S) + A_L \cdot \exp(-l/\lambda_L)$, where l is the distance of the hit position from the end of the scintillator. The short and long effective attenuation lengths are $\lambda_S \simeq 2$ cm and $\lambda_L \simeq 66$ cm for both counters, and the ratio of the amplitudes is $A_S/A_L \simeq 45\%$ for L3 and $\simeq 50\%$ for S3. The short component could be due to the light rather directly arrived at the PMs, and the long component be due to the light collected through a large number of reflections in the scintillator. A natural explanation of nearly the same attenuation length (λ_L) for the counters is that because of the large width-to-thickness ratios of 25 for S3 and 75 for L3, the scintillators are effectively equivalent to having an infinite width for the light. For ST (see Fig.9), only the second component is found from data taken with a 10 cm step. The effective light attenuation length is $\lambda_L \sim 400$ cm, which fairly agrees with the specific number of 380 cm for the BC-408 scintillator.

4.5 Effective light-velocity and position resolution along the scintillator

The effective light-velocity (v_{eff}) is deduced by the relation

$$t_- = \frac{x}{v_{eff}} + const. \quad (9)$$

Fig.10 shows a relation of $t_-(L3)$ vs. x , as an example, and Table 2 lists the resultant velocities for all counters. No appreciable difference was found for data with a 60° tilting angle. The observed velocities are nearly 10% smaller than the reported values

of around 16 cm/ns [2-8]. The position resolutions along the scintillator are obtained from the time resolution (σ_- : rms of t_-) multiplied by v_{eff} . As listed in Table 2, $\sigma_x(S3)=1.2$ cm, $\sigma_x(L3)=2.0$ cm, $\sigma_x(L4_{UD}/L4_{LR})=5.0/4.1$ cm, and $\sigma_x(ST)=0.9$ cm, where $L4_{UD}$ and $L4_{LR}$ indicate up and down and left and right PMs combinations of L4, respectively.

4.6 Position dependence of the τ centroid

Sugitate et al. [6] and Kobayashi and Sugitate [7] observed shifts of τ centroid with hit position; the centroid moves parabolically to shorten τ as the beam position departs from the center of the counter, and its magnitude is comparable to the time resolution. Fig.11 shows our t_+ centroid shifts for L1-3 in unit of each σ ; $t_+(i)$ is equivalent to $\tau(i-j)$ with $j=DF2$. No obvious parabolic behavior is observed; they are rather independent of the hit position, and their variations are much smaller than the σ 's.

4.7 High-voltage dependence of the pulse-height and time resolution

The HV dependence of the pulse-height and σ were measured; Fig.12 shows an example. The gain of H1949 increases by about 30% for every 100-V increase in HV, and $\sigma(L3)$ levels off above 2.4 kV. The same behavior was found for S3; $\sigma(S3)$ also shows a plateau above 2.4 kV. σ cannot be improved any more by increasing HV once it arrives at the level-off point. However, adding an amplifier is useful for recovering the resolution when the intrinsic resolution is not attained at the maximum HV and the minimum threshold. Fig.13 shows the threshold dependence of $\sigma(L4)$ with and without an amplifier ($\times 10$) in front of the discriminator. It is clear that with the amplifier the best resolution is achieved over a wide range of the threshold.

5. Summary

We have studied the performance of 2 mm-thick scintillation TOF counters for

relativistic particles. For a small-size scintillator of $50\text{ mm}^w \times 150\text{ mm}^l$, the counter directly coupled to PMs provides $\sigma=90\text{ ps}$, which is more than 2-times better than the achieved resolutions by the counters viewed through fishtail light-guides. Efficient light collection is crucial for obtaining higher resolution. For the larger size, $150\text{ mm}^w \times 250\text{ mm}^l$, the counter with twisted light-guides gives $\sigma=140\text{ ps}$, while the counter with fishtail light-guides gives $\sigma=216\text{ ps}$ at best. Since all of the employed PMs have sufficient time properties for the TOF measurement, the resolution was predominantly controlled by the light-collection efficiency. For the 40 mm-thick scintillator with $150\text{ mm}^w \times 1200\text{ mm}^l$, $\sigma=60\text{ ps}$ was obtained, which is a quite reasonable resolution compared to ref.[6].

With the use of S3 and ST as the start and stop counters, respectively, we can expect to attain 110 ps of overall time resolution, which could provide us more than a 7σ separation between the positrons and muons in the $K^+ \rightarrow \pi^+ e^+ \nu$ experiment.

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Figure Captions

Fig.1: Geometry of the test counters.

Fig.2: Experimental setup.

Fig.3: Time vs. pulse-height scatter plots and the projected time spectra without and with a time-walk correction for the left PM of the L3 counter. The curves in (c) and (d) show Gaussian distributions with $\sigma=10.0$ ch and 7.7 ch, respectively.

Fig.4: Scatter plot of t_L vs. t_R and time spectra in terms of t_+ and t_- for the S3 counter. The t_+ and t_- axes are also indicated in (a). The curves in (b) and (c) show Gaussian distributions with $\sigma_+=5.7$ ch and $\sigma_-=5.2$ ch, respectively.

Fig.5: R distributions for L3 and ST counters. The closed and open circles in (a) are for L3 with a tilting angle of 0° and 60° , respectively; $N_e \simeq 125$ and $\simeq 247$ are obtained from $\sigma_R = 1/\sqrt{N_e}$ (see the text). The distribution in (b) is for ST with 0° tilting angle; $N_e \simeq 1700$ is obtained. The curve shows the Gaussian distribution with respective σ_R .

Fig.6: τ spectra comprising two counters. Gaussian distributions are shown by curves with $\sigma(L2 - ST)=8.1$ ch, $\sigma(L3 - ST)=5.5$ ch, and $\sigma(L3 - S3)=6.0$ ch. in (a), (b) and (c), respectively.

Fig.7: σ vs. $t_{eff}^{-1/2}$ for S1-3 and L1-3 counters. The lines are a fit of $\sigma=(\text{constant}) \times t_{eff}^{-1/2}$ to data.

Fig.8: Hit-position dependence of σ for S3, L2, L3 and ST counters. The closed circles are for hit positions on the scintillator axis and the open circles are at 50 mm above the axis. Note that different scales are used for S3, L2 and L3 counters and ST counter.

Fig.9: Pulse-height dependence on the propagation distance l for L3 and ST counters. l is distance between the hit position and the end of the scintillator at which a relevant PM is attached. The curves are the results of fits with two

exponential components for L3 and one component for ST (see text). The resulting attenuation lengths are $\lambda_S \simeq 2$ cm and $\lambda_L \simeq 66$ cm for L3 and $\lambda_L \sim 400$ cm for ST. Note that different scales are used for the counters.

Fig.10: Obtained $t_-(L3)$ and $\sigma_-(L3)$ as a function of the hit position. The line in (a) is the result of a fit to data with $v_{eff}=14.5$ cm/ns. The dotted line in (b) indicates an average of $\sigma_-(L3)$'s of 137 ps.

Fig.11: t_+ centroid shift with hit position for L1-3 counters. The peak position of the t_+ distribution relative to that at the center of the counter is plotted in unit of each σ . This shift is equivalent to a $\tau(i-j)$ centroid shift by assigning $j=DF2$.

Fig.12: HV dependences of the pulse-height of the left PM and σ for the L3 counter. The PM is a Hamamatsu H1949: 12 stage, 26% of typical quantum efficiency with a bialkali photocathode, and 2.0×10^7 of typical current amplification at HV=2500 V.

Fig.13: Discriminator threshold dependence of σ 's for L4. σ_{UD} and σ_{LR} in (a) and (b) are obtained from up and down PMs and left and right PMs, respectively. σ in (c) is obtained in terms of $\sigma^{-2}=\sigma_{UD}^{-2}+\sigma_{LR}^{-2}$. The closed circles are the resolutions obtained with an additional amplifier ($\times 10$).

Table Captions

Table 1: Parameters of the test counters. FT and TW means fishtail and twisted type of light-guide, respectively. The L4 counter is coupled by four photo-multipliers (PMs) at four sides, while all of the others are by two PMs at two sides along the scintillator, as shown in Fig.1. The values of the typical high-voltage (HV) listed for L4 are for up, down, left and right PMs, respectively, from left to right.

Table 2: Summary of the test-counter performance. N_e , the average number of photo-electrons measured by both side PMs, is estimated through eqs.(6) and (7) (see text). η_{all} is the overall photo-electron conversion efficiency calculated as N_e/N_γ . As the effective light attenuation length, the values of the long component (see text) λ_L is presented here.

Table 1

Counter	Size (w×l×t) (mm ³)	Light-guide	PM (typical HV on left;right) (V)
S1	50×150×2	FT	R4868 (1400;1400)
S2	50×150×2	FT	H5010 (1700;1700)
S3	50×150×2	no	H1949 (2900;2300)
L1	150×250×2	FT	H5010 (1760;1760)
L2	150×250×2	FT	H1949 (2900;2820)
L3	150×250×2	TW	H1949 (2500;2600)
L4	150×250×2	FT	H1949 (3000;2800;2500;2600)
ST	150×1200×40	FT	H1949 (2000;2000)

Table 2

Counter	$\sigma(x=0)$ (ps)	N_e	η_{all} (%)	λ_L (cm)	v_{eff} (cm/ns)	σ_x (cm)
S1	379	30	0.8		15.0	5.7
S2	200	56	1.4		12.8	2.6
S3	89	240	5.9	66	13.2	1.2
L1	440	20	0.5		13.3	5.9
L2	216	75	1.9		14.9	3.2
L3	140	130	3.1	66	14.6	2.0
L4	213					
L4 _{UD}	320	53	1.3		15.7	5.0
L4 _{LR}	286	69	1.7		14.5	4.1
ST	57	1700	2.1	400	15.6	0.9

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Fig.7

Fig.8

Fig.9

Fig.10

Fig.11

Fig.12

Fig.13