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SCINTILLATORS AND PHOTOMULTIPLIERS—SOME TESTS FOR EPICS TUNE-UP

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ABSTRACT

Different scintillators and photomultipliers have been tested with respect to time and pulse height characteristics and their variation over the area of a large scintillator ($60 \times 15 \times 0.64$ cm). Using minimum ionizing particles we achieved a time resolution of 0.8 ns, a spatial resolution of 5.5 cm, and a pulse height resolution of about 15% (FWHM). Viewed from one end, the pulse height varied exponentially vs distance with a break at about 15 cm from the end. The pulse height variation across the scintillator was 10% for source positions closest to the viewed end.

I. SCINTILLATORS AND PHOTO-MULTIPLIERS

A large scintillator was tested with respect to timing and pulse height characteristics. The setup (Fig. 1) consisted of a large scintillator (I) with two strip light pipes [left (L) and right (R)] and a small scintillator (s) whose output is called the back one (B). The scintillators were illuminated with a ^{106}Rh source giving 3-MeV β -particles. Coincidence events, $1 \times s$, define the electrons to be minimum ionizing in I, i.e., the energy loss in the large scintillator is a fairly well defined quantity. It has been calculated and found to be $\Delta E = 1.2$ MeV (mean value) with a variation (FWHM) of 18% (energy straggling); for the shape of the energy distribution see Fig. 2. We performed tests using different photomultiplier (PM) tubes at the ends of the large scintillator and using different kinds of wrapping (reflecting aluminum foils or black paper). The tests can be summarized as follows:

I	EMI 9813B Tubes	Al wrapping	MCA
II	EMI 9813B Tubes	Al wrapping	PDP
III	RCA C31024 Tubes	Al wrapping	PDP
IV	EMI 9813B Tubes	Black paper	PDP
V	EMI 9813B Tubes	Al wrapping	PDP

The signals were fed into either a multichannel analyzer (MCA) or a PDP-11 computer (PDP). In

Fig. 1.
Sketch of setup, coordinate system, and electronic schemes.

Fig. 2.

Examples of pulse height spectra for the left (L) and right (R) side tubes, and for the sum (L+R) and difference (L-R). The source position was $(x,y) = (0,0)$ and the results refer to Test IV. The bottom part shows the straggling distribution for 2-MeV electrons incident on a 0.64-cm-thick scintillator; the energy loss is 1.2 MeV (peak value) and the width 0.22 MeV (FWHM).

In Test I the tubes were operated at high voltage (~ 2400 V) giving dynode pulses about 4 V high. In this test the tubes exhibited a nonlinear performance and the observed pulse height variations were scaled up 40% to correct for this effect.

The mapping was performed by moving the large scintillator while maintaining the small one and the source in a fixed position. The coordinate system used to define the source position relative to the large scintillator is shown in Fig. 1.

II. TIMING INFORMATION FROM THE SCINTILLATOR

A. Different PM Tubes

Two PM tubes were used: A fast 5-stage tube (RCA C31024, risetime ≤ 1 ns, gain $\sim 5 \times 10^6$) and a standard 14-stage tube (EMI 9813B, risetime ~ 2.4 ns, gain $\sim 5 \times 10^7$). In order to learn about the

limitations in the electronics of the setups, we used small-sized scintillators attached directly to the entrance window of the tubes. Placing a ^{60}Co source between two such detectors we obtained a γ -e coincidence time resolution of 270 ps and 370 ps with RCA and EMI tubes, respectively; oscilloscope traces indicated risetimes of ≤ 2 ns for the RCA tubes and ≈ 4 ns for the EMI tubes.

B. Time Resolution for the Large Scintillator

The time resolution was measured for the setup shown in Fig. 1, i.e., we recorded the time difference for the signals from the two ends of the large scintillator, $T_L - T_R$, and the differences $T_L - T_B$ and $T_R - T_B$ (B refers to the small back scintillator); from the latter quantities we obtain the sum $T_L - T_B + T_R - T_B = T_L + T_R - 2T_B$, which is constant for a fixed distance between the scintillators and for a given time of flight (TOF) for the triggering particles.

An early test (I) using the EMI tubes and timing with respect to the leading edge of the signal gave a resolution of 670-820 ps (mean value of 770 ps) for both $T_L - T_R$ and TOF. The anode pulses were in this case close to saturation (pulse height 8-10 V) using an applied high voltage of ~ 2400 V. The time resolution showed no apparent variation with the source position (see Fig. 3). In later measurements with the EMI tubes run at a lower voltage (~ 2050 V) we could not get better resolution than 950 ps with EMI tubes and leading-edge timing, and this result was found to be very insensitive to changes in the applied high voltage and the discriminator level setting. With zero-crossing timing it was always possible to obtain a resolution of ≈ 750 ps by using very high voltages (~ 2400 V) giving saturated anode pulses.

Using RCA tubes, a resolution of 650 ps (for $T_L - T_R$) was obtained using leading-edge timing with ~ 200 -mV pulses and the timing threshold at 30 mV. No improvements were found by using zero-crossing.

The time resolution for different values of the pulse height was also studied. No clear correlation was observed between the time resolution $T_L - T_R$ vs $V_L + V_R$ or $V_L - V_R$ for a resolution in the range of 800-900 ps (cf. below).

The time resolution was checked for signals transported through long cables. A transport distance of about 70 m had no deteriorating effect on a time resolution of about 800 ps.

The type of wrapping used for the scintillator seems also not to affect the time resolution. Using black paper or reflecting aluminum wrapping gave for both cases a resolution of about 800 ps.

Fig. 3.

Top: Time difference plotted vs x for $y=0$ and $y=7$. The results refer to Test I. Bottom: Time resolution plotted vs x for $y=0$ and $y=7$.

C. Mapping of Time vs Source Position (x,y)

Results of the time difference ($T_L - T_R$) and TOF ($T_L + T_R - 2T_B$) vs (x,y) are shown in Fig. 3. $T_L - T_R$ is a perfect linear function of x , which is also true for TOF. The TOF, however, shows a walk of 0.6 ns between $x = -30$ and $x = +30$ for both $y=0$ and $y=7$. The walk is probably caused by a difference in gain between the left- and right-hand tubes. A later test with carefully balanced tubes showed (cf. Fig. 4) that the TOF is constant over the whole scintillator within ± 0.1 ns (the distance between the scintillators was probably kept at no better accuracy).

The correlation between $T_L - T_R$ and $V_L + V_R$ was studied and some results are shown in Fig. 4 (bottom). No correlation was found for a source position in the center of the scintillator but was found at the ends. One may also note that $T_L - T_R$ does not vary with a change in the y -coordinate.

Fig. 4.

The time difference $T_L - T_R$ plotted vs pulse height $V_L + V_R$ for different source positions. The results refer to Test III.

III. SPATIAL INFORMATION

The linear dependence of $T_L - T_R$ on the x position allows a determination of x by measuring the time difference. The obtained time resolution of 770 ps (Test I) corresponds to a spatial resolution of 5.5 cm (FWHM). The effective speed of signal (the apparent speed of light) is then about 14.4 cm/ns.

IV. THE PULSE HEIGHT INFORMATION FROM THE SCINTILLATOR

A. Pulse Height Spectra

Examples of pulse height spectra are shown in Fig. 2 for the left and right tubes and the sum. The peak widths are 41, 41, and 34% (FWHM which is estimated from 2.35σ). Part of the peak broadening comes from the energy straggling (x) whose distribution is shown in the lower part of the same figure ($s = 18\%$, FWHM). The rest of the observed peak width is ascribed to the statistical fluctuations ($2.35/\sqrt{n}$ C, FWHM) in the effective number of photoelectrons (n). The straggling affects both phototubes equally which then gives rise to a correlated variation in contrast to light statistics which result in an uncorrelated variation. For the case that the pulse

heights V_L and V_R have the same mean values, the spectrum $V_L \sim V_R$ should only reflect the uncorrelated fluctuations in V , i.e., the peak width (W) should be determined by

$$W = \frac{2.35}{\sqrt{n}}, \quad (1)$$

where n is the total number of photoelectrons, $n = n_L + n_R$. The $V_L - V_R$ spectrum of Fig. 2 shows a peak width of 21% from which we determine n to be 122. From this figure we can estimate the other kinds of contributions (X) to the observed peak widths of V_L , V_R and $V_L + V_R$ from

$$W^2 = X^2 + \left(\frac{2.35}{\sqrt{n}} \right)^2, \quad (2)$$

which gives $X \approx 27\%$; most of this is due to the straggling.

The $V_L - V_R$ spectrum can be used to estimate n as long as we know n_L/n_R . For a nonsymmetric source position, $x \neq 0$, one can measure V_L' and V_R' (with $V_L = V_R$ at $x = 0$) and $V_L - V_R$ and $V_L + V_R$ (after adjusting the left and right-hand side gains so that $V_L = V_R$ at the actual source position). From

$$\frac{n_L + n_R}{(n_L + n_R)^2} = \left(\frac{W}{2.35} \right)^2, \quad (3)$$

we then obtain

$$n = \frac{1}{\left(\frac{W}{2.35} \right)^2} \frac{1}{1 + \frac{V_L'}{V_R'}} \quad (4)$$

setting $n_L = n$ and $n_R = (V_R'/V_L')n$ in Eq. (3); V_L' and V_R' are the pulse heights for the gains set so that $V_L' = V_R'$ at $x=0$.

B. Mapping of Pulse Height vs Position.

The results of Test IV are shown in Fig. 5. Both V_L and V_R show a simple exponential variation with x over the central region of the scintillator. Ten to fifteen centimeters from the end of the scintillator there is a break in the pulse height variation so that closer to the end the pulse height seems to be determined by another exponential function. We then find that the pulse height of each side is well described by two simple exponentials $V = V_0 e^{x/\lambda}$, where V_0 and λ take different values in the near-end region (i.e., $x < -20$ for the left side and $x > 20$ for the right side). The results are summarized in the table below.

As can be seen, the left- and right-hand sides appear to have different attenuation lengths. This apparent asymmetric property of the counter is not understood. It also seems that a reflecting wrapping of the scintillator (Tests II, III, and V) increases the attenuation length as compared to black paper wrapping (Test IV).

In the case the left and right pulse heights are determined by the same exponential function, the product $V_L \times V_R$ is a position (in x) independent quantity in the central part of a long scintillator or over the whole region of a short one not exceeding about 25 cm. This is further discussed in Sec. V.

The variation of pulse height vs y for different x was studied and some examples of results are shown in Fig. 6. The significant y variation occurs for the pulse height from the near end (about 9% at $x = -27.5$). The results shown are from Test IV with no aluminum wrapping of the scintillator. A variation of $\leq 6\%$ was observed in Test II (at $x = -20$) with the

SUMMARY OF PARAMETERS DETERMINING $V = V(x) \propto e^{x/\lambda}$

Test No.	λ_L (In the far-end region)	λ_R	λ_L/λ_R	λ_L (In the near-end region)	λ_R	λ_L/λ_R
I ^a	-134.0	80.4	1.67	-27	36	0.75
III	-82.7	68.5	1.21	-27	28	0.96
IV	-60.7	55.6	1.09	--	--	--
V	-77.0	63.5	1.21	-32	--	--

^aThese results are affected by the nonlinearity in the PM tube response.

aluminum wrapping. The results of Test I (see Fig. 7) were consistent with this; taking into account the nonlinearity in the tube response in this case, the observed variations should then be scaled up about a factor of two. A common wrapping around all strip light pipes (Test V) appears to give a result consistent with that of Test IV.

C. Pulse Height Resolution vs Position

The resolution varies in x in such a way that it is significantly better at the near end than at the far end. This obviously reflects the different numbers of effective photoelectrons. From the observed peak widths in the pulse height spectrum the number of photoelectrons was calculated using Eq. (2) (where the energy straggling X is assumed to be 18% FWHM); it should be noted that this is probably too low a number and the use of a larger value would have implied a stronger variation with X . The results of such a calculation are shown in Fig. 5.

Fig. 5.

Top: Pulse height for the left-and right-side tubes plotted vs x position ($y=0$). The solid lines are exponential fits to the data. Bottom: The effective numbers (n) of photoelectrons calculated from the observed peak width; n is plotted vs x and compared with the pulse height variation (solid lines). The results refer to Test IV.

Within the uncertainty, the extracted number of photoelectrons appears to follow the pulse height variation vs x .

V. PHOTON COLLECTION AND TRANSMISSION EFFICIENCIES IN THE COUNTERS

It was pointed out above that a reflecting aluminum wrapping around the scintillator seems to help increase the attenuation length; the improvement is about 25%. Significantly better light collection was also found when using aluminum wrapping; compared to black paper wrapping the improvement was about 30%. From the width of the peak in the $V_L - V_R$ spectrum, the number of effective photoelectrons in one tube is found to be 125 [average value for $(x,y) = (0,0)$]. For the left side the

Fig. 6.

Top: The pulse height variation vs x for different y . Bottom: The pulse height variation vs y for $x=-27.5$. The results are for Test IV.

Fig. 7.

Pulse height variation vs y for different x . The results are from Test I, and the observed variations should be scaled up about a factor of two to account for the nonlinearity of the tubes. The summed pulse height ($L+R$) is arbitrarily normalized.

pulse height variation can be reproduced by $V = V_0 e^{x/\lambda}$ with $V_0 = 331$ and $\lambda = -83$ for $x > -20$, and with $V_0 = 208$ and $\lambda = -27$ for $x < -20$. Letting this represent the variation in the number of photoelectrons (n) results in $n = 260$ at the near end of the scintillator. If it is assumed that the quantum efficiency of the PM tube is 25% and that one photon is created for each 100-eV energy loss, a light collection efficiency of $260 \times 100/0.25 \times 1.2 \times 10^6 = 9\%$ is obtained for the near-end tube.

The results of a few other measurements on scintillator counters are summarized in the table below.

Common to all measurements is the fact that they show a break in the pulse height variation 10-15 cm from the near-end tube. Since the counter dimensions are quite different in the four cases, this feature is probably a property of plastic scintillators.

The plastic is dispersive, causing a stronger attenuation of light in the short than in the long wavelength region. This provides a possible explanation to the pulse height variation at short distances

from the light pipe of a scintillator. From the results in the table, one is also inclined to conject that the attenuation length does not change dramatically with the thickness of the scintillator.

VI. NUMBER OF PHOTOELECTRONS AND PERFORMANCE OF THE COUNTER

The relation between the number of photons n and the peak width of the pulse height spectrum was indicated above. Less evident is the relation between the timing performance and n . Some interesting results on this question can be found in Ref. 4 which are quoted in Fig. 8. These show that the time resolution improves proportionally to $\sqrt{n}$ to a certain limit which is set by the dimensions of the scintillator; this limit increases with increasing size.

VII. CONCLUSIONS

In the tests of large scintillators ($60 \times 15 \times 0.64$ cm) with two light pipes, a time resolution of better than 1 ns was demonstrated; the best result for the time difference between the two ends is 650 ps with fast RCA tubes and 750-950 ps with standard EMI tubes. This corresponds to a spatial resolution of ~ 5.5 cm in the determination of the position of the event along the counter. Using the information from the two ends, a position-independent time of flight to another scintillator can be determined within about ± 0.2 ns. Each event deposits an energy loss of 1.2 MeV in the scintillator. This energy loss was found to give 260 effective photoelectrons at the position closest to the light pipe corresponding to a pulse height resolution of 15% (FWHM). The pulse height was found to obey an exponential function of the distance from the end (x) determined by $e^{-x/\lambda}$ where $\lambda \approx 28$ for $x \leq 15$ and $\lambda \approx 69-82$ for $x > 15$. The product of the left and right-side pulse would then be

SUMMARY OF λ PARAMETERS FITTING THE PULSE HEIGHT VARIATION, $V = V_0 e^{x/\lambda}$

Measurement	Scintillator		λ	
	Dimensions (cm)	Material	Near-end region	Far-end region
This test No. III	$65 \times 15.7 \times 0.63$	Pilot F	27-28	69-82
Dahlgren <i>et al.</i> ¹	$50 \times 27 \times 0.4$	Pilot B	23-25	64-68
Charpak <i>et al.</i> ²	$40 \times 12 \times 1$		~ 30	~ 62
Crabb <i>et al.</i> ³	$18.6 \times 6 \times 0.6$		~ 20	--

(a) Time-of-flight resolution versus position along the 1 cm thick counter for various beam momenta. (b) Time-of-flight resolution versus position along counters of different thickness. (c) Pulse height versus position along the 1 cm thick counter for various beam momenta. The bars indicate the fwhh resolution obtained with pulse-area analysis. The values obtained with a 5 cm thick slab are also reported.

Position resolution versus distance between PMs as from table 1 compared with other results. The resolution is a factor 10 worse when the distance increases by a factor 100.

Fig. 8.

All information on this page is taken from Ref. 4. Used with the permission of the North-Holland Publishing Company and J. Eades.

independent of x for a small length (<30 cm) and for a large scintillator in the region more than 15 cm away from the ends.

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