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I. Summary

A large variety of nanosecond-response, high-gain phototubes for use in high-energy particle detectors is available to users. The time spread, gain, and noise properties of such tubes are important to know for selection of a suitable type. The 24 to 30% quantum efficiency of phototubes containing bialkali photocathodes for instance, along with their low noise offered at gains up to 3×10^7 make them especially desirable in Cerenkov counters. We present measurements of single-electron time spread for several 8575's, 56AVP's, 6810's, C70133's, 2067's, and 7264's. Using the measuring equipment, voltage ratios in the focus-electrode system for optimum collection and minimum time spread were found. A description of the measuring system is included. Two alternative ways of expressing the time spread are given. All tubes were magnetically degaussed and were shielded for these measurements.

II. Introduction

When a short pulse of light strikes the photocathode of a photomultiplier tube, photoelectrons are released, and an amplified pulse of electrons is expected to arrive at the anode a short time later. The average time difference between the light flash and the resulting anode pulse is called the transit time of the tube. Because of the statistical processes involved, there are random deviations in the transit times measured for individual pulses. These random deviations affect the accuracy with which one may measure the time of occurrence of a single light pulse.

The spread or uncertainty in the delay time between illumination and output pulse is a function of the amplitude of the light signal as well as phototube parameters. Since the time spread, τ_s, varies inversely as the square root of the number N of photoelectrons, $\tau_s \propto N^{-\frac{1}{2}}$, it is largest at weak light levels. From the foregoing it is clear that, given the phototube time spread for single photoelectrons, one can calculate the behavior for larger values of N.

It is rather difficult to measure the mean value of N if N is greater than 1, but fortunately the single-electron case, N = 1, can be explored rather easily by using a very low light level. To produce single-photoelectron events from light flashes, sufficient optical attenuation is placed between the light pulser and photocathode so that on the average, only two or three anode pulses are obtained per 60 light-pulser flashes.[1]

*Work sponsored by the U. S. Atomic Energy Commission.

If the time difference between arrival of an anode pulse (resulting from a single photoelectron) and light signal is measured for a large number of light flashes, the relative number of output pulses occurring in each unit interval following the light signal may be plotted as a histogram. Figures 1A and 1B are for 2067 and 8575 phototubes, respectively, and serve to demonstrate curves for single photoelectrons. The dots are 0.1 nsec apart, the brighter dots being 1.0 nsec apart.

When one uses tubes at the lowest light levels, the photoelectron collection efficiency is of special interest. Since adjustment of phototube potentials in general varies both time spread and collection efficiency, I have included relative-collection-efficiency data in this paper.

A. Sources of Time Spread

When considering the sources of time spread in a photomultiplier, one may think separately of two distinct physical regions:

(a) The cathode-to-first-dynode region (input electron optics).

(b) The multiplier and output structure.

First consider (a). In general, time spread in the input electron optics results from several separate effects. It is a function of the position on the cathode from which the photoelectrons leave, the spread in initial emission velocities, the voltage applied to the cathode, cathode focusing electrodes (if any), and the first few dynodes. These voltages and the voltage distribution must be specified, since time spread varies as the inverse square root of the voltage. Measurements were made using manufacturers recommended voltage-divider networks. The entire cathode area of the phototubes was illuminated during the tests.

Less need to said concerning (b), except that the multiplier contribution to overall time spread varies essentially as the square root of $V_{multiplier}$. Thus the highest possible overall voltage would be desirable to minimize time spread, but usually the need to obtain a given gain or low noise is an overriding consideration in determining multiplier voltage. The voltages I used were typical of those desired for low-light levels and are given in each figure.

B. Collection Efficiency for Single Photoelectrons

Not every photoelectron ejected from the photocathode gives rise to an output pulse, especially considering that the potential distribution in the input electron optics is to be varied as a part of the measurement. Thus we must speak of relative collection efficiency, (RCE), where

$$\text{RCE} = \frac{\text{efficiency of counting light flashes at any lens potential}}{\text{efficiency of counting light flashes at optimum lens potential}} .$$

Note that RCE is independent of photocathode quantum efficiency (pqe), since pqe appears in both the numerator and denominator. Needless to say, many phototube users will wish to select lens potentials to maximize RCE, provided the time spread is acceptable. In what follows, we discuss how time spread and RCE vary with lens potential.

III. Collection-Efficiency Measurements

A. Single-Electron Counting

Data showing the relative collection efficiency vs focusing-electrode potentials are shown in the solid curves of Figs. 2 through 6. Figure 7 shows a block diagram of the system for measuring relative collection efficiency.

The light level of a mercury-capsule light-pulse generator[2] was adjusted to generate predominantly single-photoelectron events. The anode discriminator pulses from the phototube under test were put in coincidence with electrical signals from the light pulser synchronous with the flash. As mentioned later in section IV, the discriminator was set sufficiently sensitive to count all pulses irrespective of amplitude over an amplitude range of greater than 100 to 1. The tube gain in turn was set to center the anode amplitude distribution within the discriminator sensitive range. Discriminator pulse widths, of course, were adjusted to be wide enough to produce overlap despite time jitter. The signal from the light-pulser discriminator in coincidence with the phototube acts as a gate and reduces the phototube noise pulse rate. In fact, the noise pulse rate allowed by this gating operation is only about 3×10^{-6} the ungated noise rate, since 3×10^{-6} is the fractional <u>on</u> time of the light pulse channel.

Since the anode discriminator is insensitive to input amplitude, moderate gain changes do not affect the counting rate, and the counting rate will be proportional to the collection efficiency at various focus-electrode potentials, since the light level is maintained constant.

B. Single-Electron Counting vs Average Current

For some phototubes, there is an important distinction between the operating point for optimum collection of single photoelectrons and the adjustment for maximum average anode current under weak photocathode illumination. The dotted curve of Fig. 6 illustrates the observed effect. The rather symmetrical convex curve showing peak collection near V_{K-FE}/V_{K-D_1} = 76% refers to a maximum in the average anode current under continuous weak illumination of the photocathode. An identical curve results when one uses weak light, chopped at 100 pulses/sec, and maximizes the fundamental chopping frequency output by lens-potential adjustment. Contrast this with the sloping line maximizing at V_{K-FE}/V_{K-D_1} = 100%, which is the curve obtained when counting single electrons according to the procedure of Fig. 7. It is clear that for some phototubes the lens potentials cannot be optimally adjusted without the time-coincidence arrangement; maximizing tube output on an average-current basis leads to a spurious setting.

A plausible explanation (which has not been completely verified for lack of time) for the observed effect is that the optimum setting under dc illumination and no coincidence is one for which there are appreciable numbers of delayed pulses. These delayed pulses, whatever their origin, appear in the average anode current but are excluded from the coincidence system's output, hence the difference in lens-potential settings obtained under the two different conditions.

An entirely different explanation for the observed effect is the possibility that some electrons from a portion of the photocathode strike a focus electrode, liberating secondaries, some of which reach dynode one. This "adventitious dynode" theory has not been checked, but could be by illuminating small areas of the photocathode and comparing the dc with the time resolved collection efficiencies.

It should be noted that some tubes exhibit this effect and others do not; so far, no method is known of predicting whether or not a given tube type is susceptible without testing it.

IV. Transit-Time-Spread Measurements

The dashed-line curves of Figs. 2 through 6 represent the average single-electron time-spread measurements made on several samples of each type of phototube evaluated. The effect on collection efficiency of focus-electrode potential change is shown by the solid curves.

Any system used for measuring phototube time-spread parameters must be free of timing errors which are contributed by the associated electronics to assure that results are representative of the tube itself, and not the composite of the phototube and electronics. Figure 8 is a block diagram of the system used for this test. The phototube discriminator plays the dominant role in preventing system timing errors.

Since the light-pulse attenuation is adjusted to give single photoelectrons as described earlier, the photomultiplier's first dynode receives single electrons. Dynode two in turn receives some number of secondary electrons δ which, though an integer, varies from pulse to pulse. The repetition of this process through all dynode stages results in a final output pulse whose amplitude varies statistically from pulse to pulse. It is these output pulses, whose amplitude varies over a wide range, that must be timed. Using zero-crossing[3] and zero-biased threshold-discriminator techniques, timing signals having less than 0.2-nsec error over a dynamic amplitude range of 100 to 1 were produced.[4] A clipping stub placed at the anode of the phototube differentiates the output pulse producing a zero-crossed signal. The zero-crossing point of the signal was detected in a discriminator whose threshold was shifted to zero at the correct moment by a pedestal produced from a signal taken from the last dynode. Because the standardized output pulse from this discriminator now contained the timing information without suffering statistical fluctuations of pulse amplitude and shape, the demands on subsequent electronics were eased. This output pulse was used as the stop input of a time-to-height (t-h) converter, the start pulse was taken from the light pulser. The output of the t-h converter was fed to a pulse-height analyzer (PHA). The data could be read out onto punched paper tape or displayed on an oscilloscope.

V. Data Analysis of Time Spread

To ease the analysis of the PHA data, the punched-paper-tape output was fed to an off-line PDP-5 computer specifically programmed to analyze the time spread in two basic ways. The first was to look for the usual fwhm points on the curve. Typically, the curve was spread out over 80 to 100 channels of the PHA. Ideally, one should run the data collection for a very long time to obtain a smooth curve with a precisely located peak, but practical considerations ruled out this procedure. To introduce some smoothing, the program used the average of the four highest channels to represent the peak of the curve. Using this number, the program looked in both directions to find the channels containing the nearest to one-half of the peak number, reporting the absolute channel numbers and the number of channels between the two half-peak amplitude points.

Since the shape of the single-electron time-spread curve is not simple (see Fig. 1B) and furthermore varies with lens potentials, the narrowest fwhm is not necessarily the optimum tube operating point. We therefore discuss another method.

The second method of analysis is one that may give phototube users a more realistic number for comparison of tube types. Suppose, as is often the case, the object is to observe weak light flashes with a given efficiency in the narrowest possible time slot. Then, the desired information about tube performance is not fwhm (the distance between two points on the time-spread curve) but some knowledge of how the area under the time-spread curve is distributed. I have chosen to define as the significant parameter the minimum width of time slot which (properly centered) permits 50% of all output pulses to be counted. Table I presents the 50% efficiency times, τ_{50}, for a variety of tubes and gives the typical lens potentials, overall voltage, and gain for obtaining these times, as well as the RCE. Further, the sensitivity to misadjustment of lens potentials is noted in the last column.

VI. Conclusions

1. Considerable effort is required on the part of an individual user to produce data of the type presented here, especially if the user wants to evaluate several different tube types. Over the years, users throughout the world have continued to make such measurements to meet their requirements. I propose that manufacturers measure the single-electron time spread and RCE over a range of focusing voltage ratio, as was done here, and present the results as commercially available characteristic curves so all users have access to the data. Lens potential curves are much more descriptive than is a single operating point, especially in giving information about tube sensitivity to slight misadjustment of voltage.

2. One may remark regarding future phototube developments, on the basis of the measurements presented here. As a class, the tubes studied exhibit a transit-time spread of a few nanoseconds. Indeed, the tubes tested are in the range of 2 to 4 nsec. Considering design differences, this is a surprisingly narrow range, suggesting that the tubes are more alike than different. To a user needing a tube tenfold faster, it is clear that new designs are required. Perhaps interest will be stimulated in developing phototubes that are less limited by front-end optics than present tubes, and thus are more effective in fast light detection.

3. The experience I had concerning RCE indicated that it is not wise to tune the V_{K-FE}/V_{K-D_1} ratio for maximum anode current with a dc light source if timing is important (see Fig. 6). The conclusion is that one should adjust the lens potential in a system similar to that which will actually be used. This procedure will avoid spurious settings which may occur otherwise.

VII. Acknowledgments

I wish to thank Mr. S. W. Kale for his help in collecting data, and Mr. B. R. Borgerson for his help with the computer program.

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Table I. Table of 50% efficiency times (τ_{50}) at typical voltage and gain settings.[a]

Tube type	τ_{50} (nsec)	Typical ratio $\frac{V_{K-FE}}{V_{K-D1}}$	V_{A-K}	Gain	Relative collection efficiency (%)	Notes to user
6810 A	2.3	0.85 - 0.90	2200	6×10^{7}	95 - 100	
7264	1.9	0.85 - 0.95	2000	3×10^{7}	88 - 100	
2067	1.4	----	1700	3×10^{6}	----	No adjustable focus electrode
8575	1.5	0.80	2500	5×10^{7}	98	
56 AVP	1.3	0.04	2500	8×10^{7}	90	Requires critical adjustment of focus electrodes
C70133	2.5	1.0	2800	4×10^{7}	100	Adjust for maximum collection efficiency rather than minimum time

[a] Full cathode illumination. All tubes degaussed and magnetically shielded.

Figure Legends

Fig. 1. (A) Typical curve of time spread resulting from system measuring a 2067. (Note time goes from right to left.)
(B) Time spread curve of a 8575 (lens potentials not optimized).

Fig. 2. Relative collection efficiency and fwhm time spread vs focus-electrode potentials for 6810A phototubes.

Fig. 3. Relative collection efficiency and fwhm time spread vs focus-electrode potentials for 7264 phototubes.

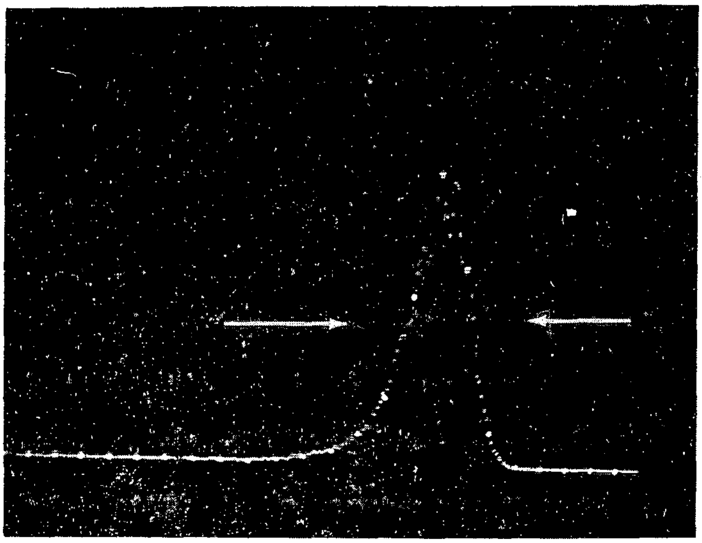
Fig. 4. Relative collection efficiency and fwhm time spread vs focus-electrode potentials for 56AVP phototubes.

Fig. 5. Relative collection efficiency and fwhm time spread vs focus-electrode potentials for 8575 phototubes.

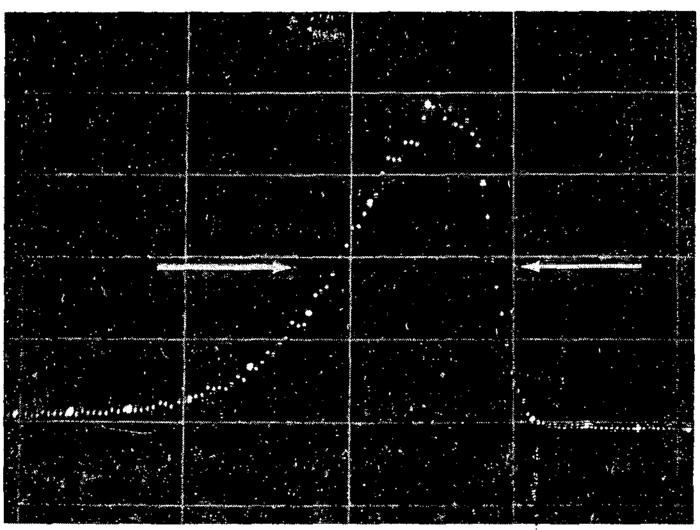
Fig. 6. Relative collection efficiency and fwhm time spread vs focus-electrode potentials for C70133 phototubes.

Fig. 7. Block diagram of system for measuring relative collection efficiency.

Fig. 8. Block diagram of system used for transit-time measurement. Computer was used off-line.



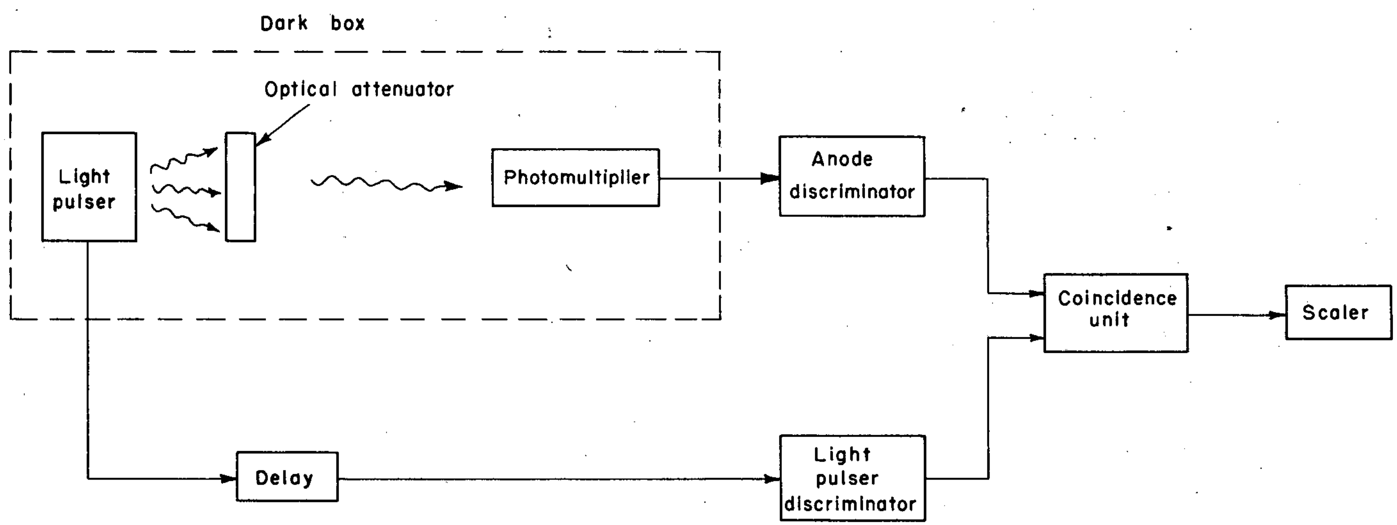
RCA 2067
1700 V_{A-K}
fwhm 2.4 nsec



RCA 8575
2500 V_{A-K}
$\frac{V_{K-FE}}{V_{K-D_1}} = 92\%$
fwhm = 2.7 nsec

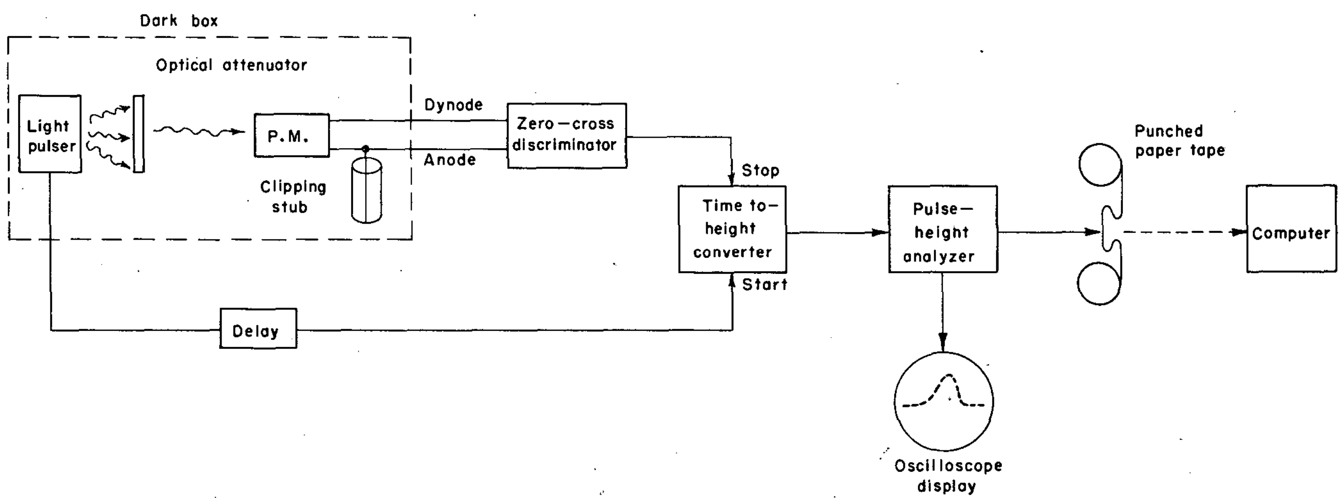
ZN-5946

Fig. 1



MUB-13058

Fig. 2



MUB-13059

Fig. 3

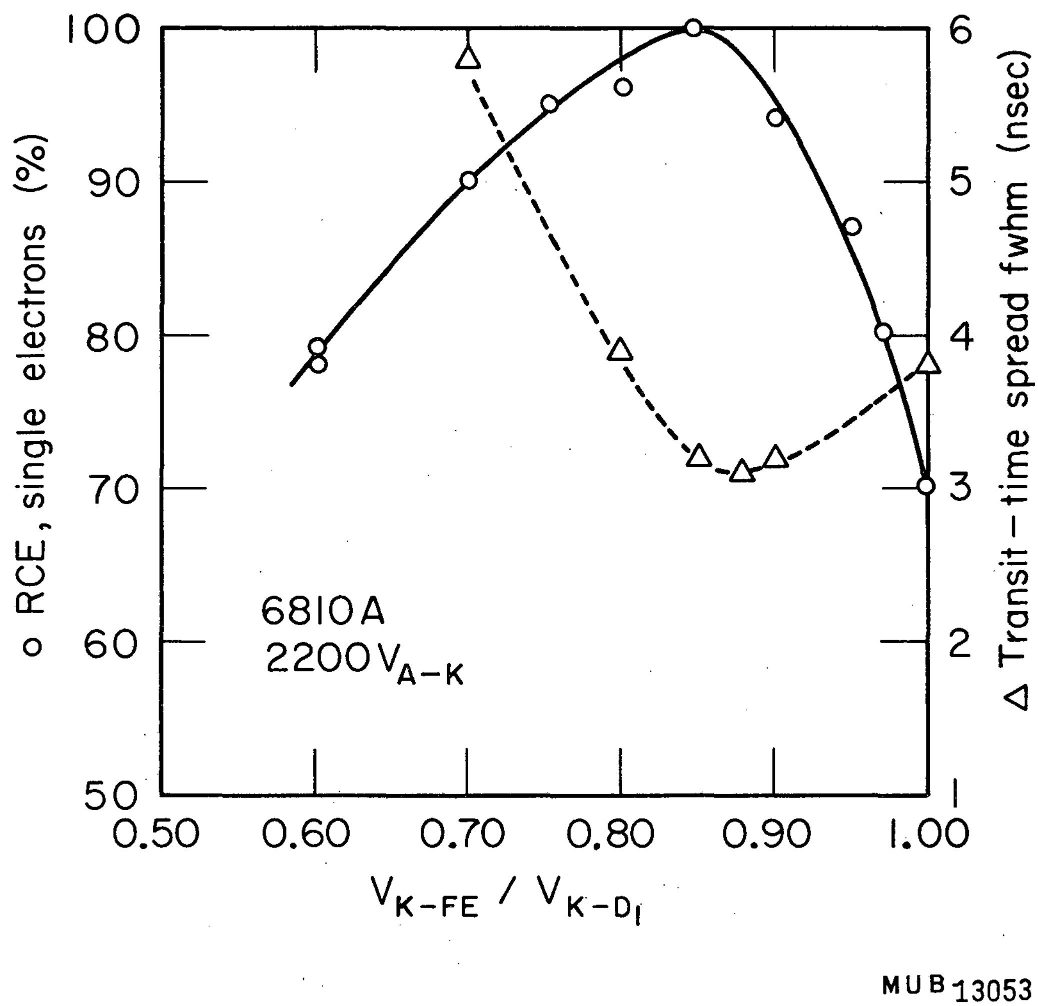
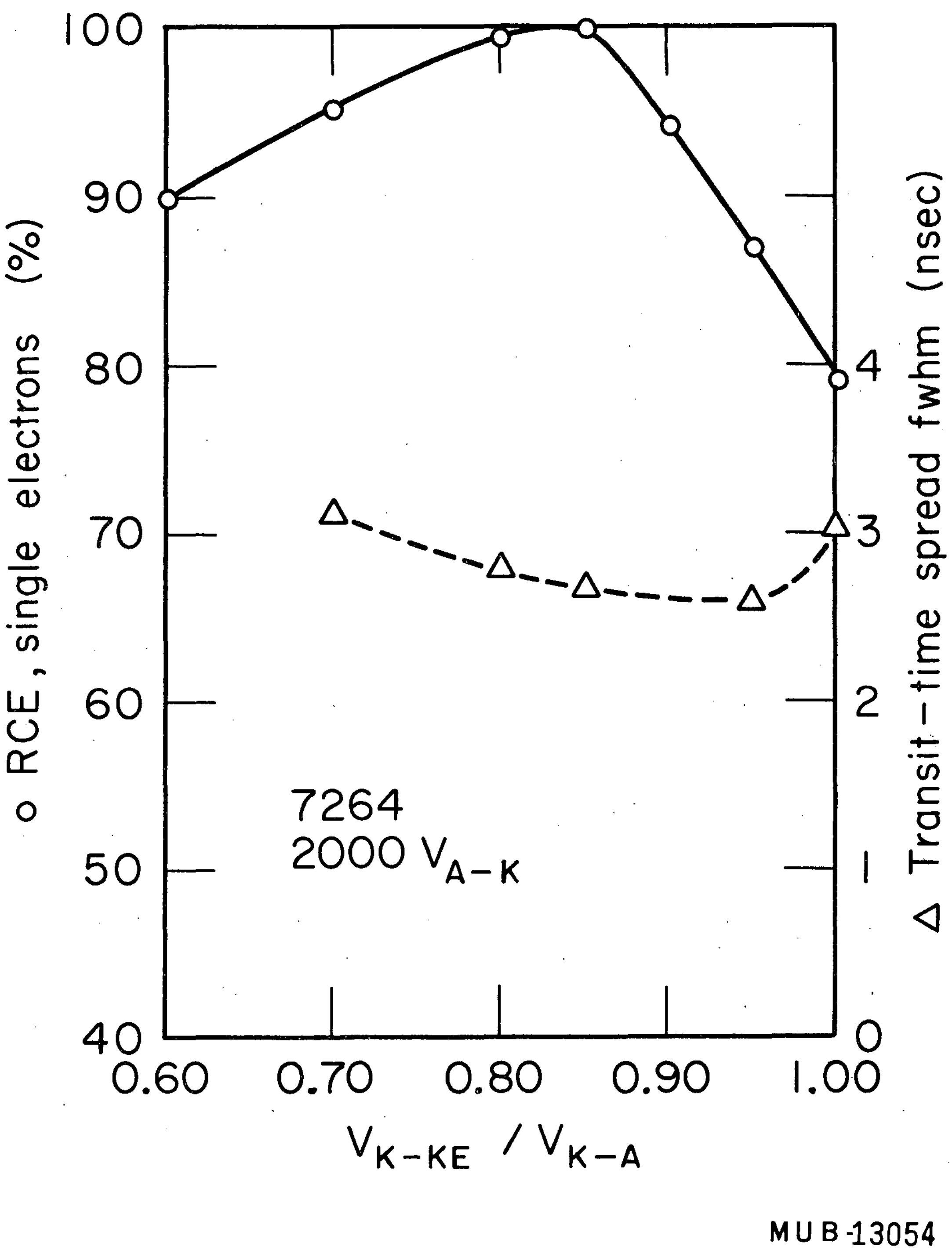
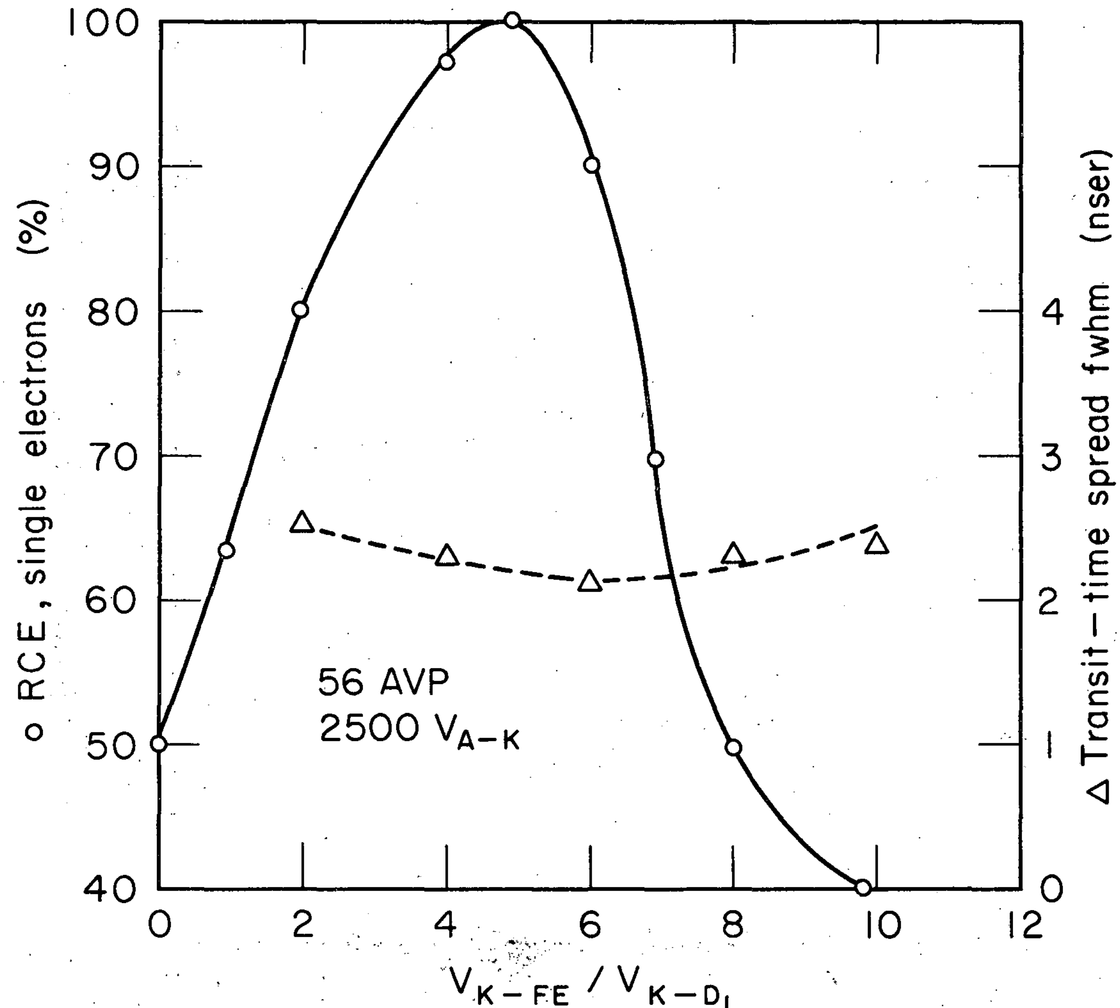

100
90
80
70
60
50
6
5
4
3
2
1
0.50
0.60
0.70
0.80
0.90
1.00
o RCE, single electrons (%)
Δ Transit - time spread fwhm (nsec)
6810A
2200V A-K
V K-FE / V K-D1
MUB 13053

Fig. 4



100
90
80
70
60
50
40
0.60
0.70
0.80
0.90
1.00
4
3
2
1
0
○ RCE, single electrons (%)
△ Transit-time spread fwhm (nsec)
7264
2000 V A-K
V K-KE / V K-A
MUB-13054

Fig. 5



MUB-13055

Fig. 6

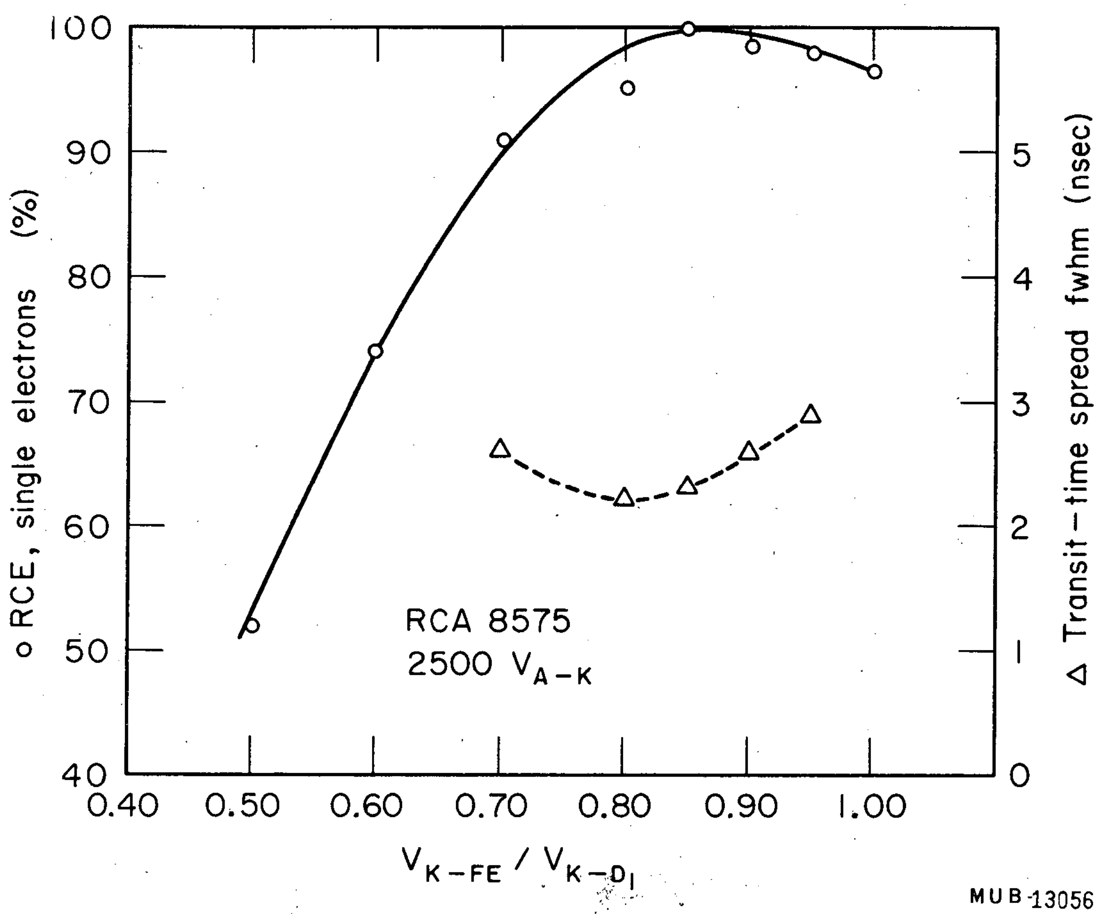

100
90
80
70
60
50
40
o RCE, single electrons (%)
5
4
3
2
1
0
Δ Transit - time spread fwhm (nsec)
RCA 8575
2500 V_{A-K}
0.40 0.50 0.60 0.70 0.80 0.90 1.00
V_{K-FE} / V_{K-D_1}
MUB-13056

Fig. 7

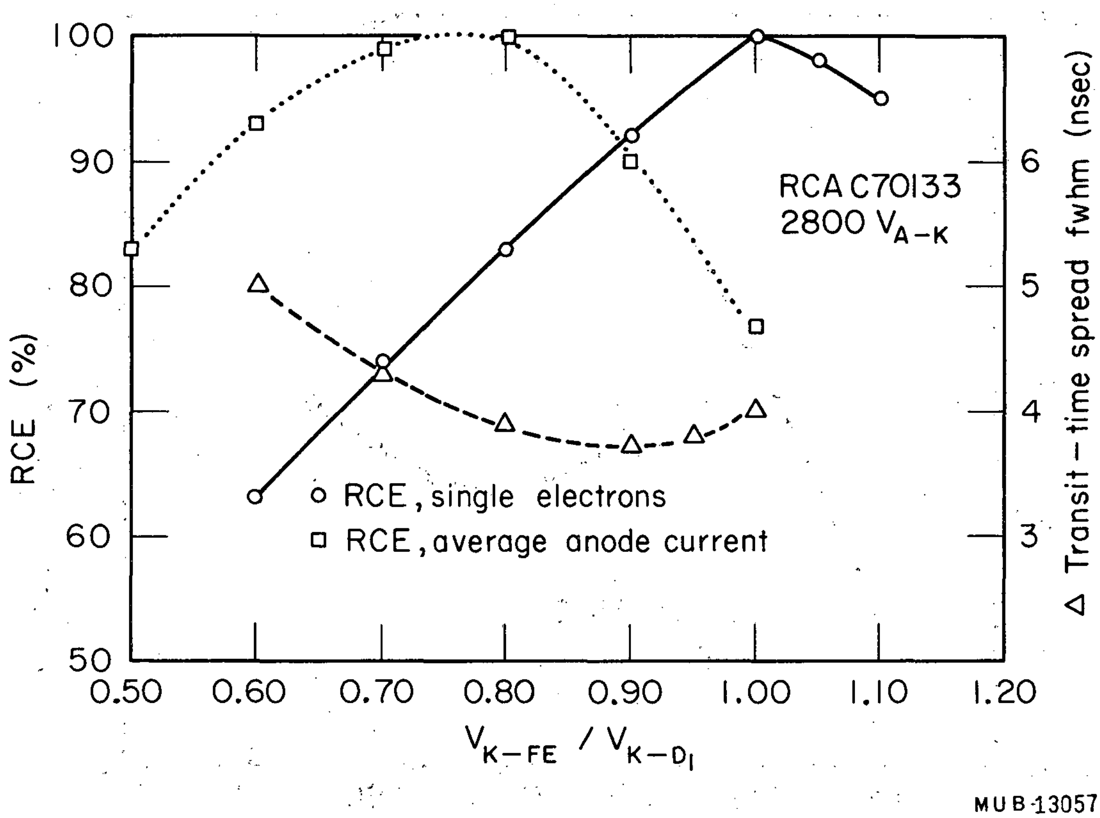

100
90
80
70
60
50
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
RCE (%)
6
5
4
3
Δ Transit-time spread fwhm (nsec)
RCA C70133
2800 V_{A-K}
○ RCE, single electrons
□ RCE, average anode current
V_{K-FE} / V_{K-D_1}
MUB-13057

Fig. 8