

# LIMITS OF SENSITIVITY OF LIQUID SCINTILLATION COUNTERS\*

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ALTHOUGH the efficiency with which the liquid scintillator converts high-energy radiation into light determines the final limitation in sensitivity, much depends upon the efficiency with which the resulting optical signal is utilized. In order to complete the picture, the light must be extracted from the

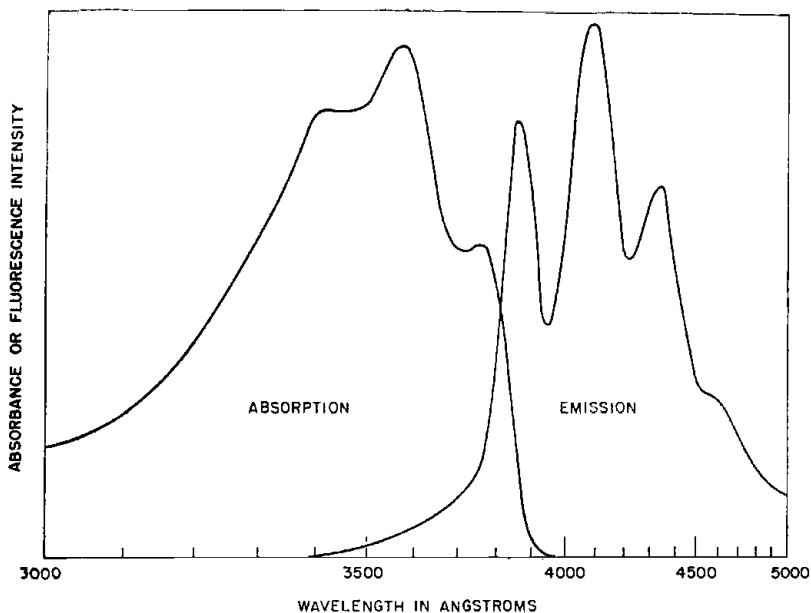


Fig. 1. Absorption and emission spectra for POPOP in *cyclohexane*. The emission spectrum is for an extremely dilute solution and is uncorrected for the response of the spectrometer

scintillator and utilized to produce an electrical signal. The electrical signal must then be amplified and processed in an appropriate way to provide the desired information.

The first requisite is to get the light out of the scintillator. Fortunately, this can be done successfully. Most scintillators do not absorb their own radiation

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to an extent which limits the ability to get light out of thick specimens. This is not to say, however, that there is no reabsorption. Almost all of the solutes customarily used in liquid scintillators reabsorb a portion of their own radiation. This is illustrated in Fig. 1 which shows the absorption and emission spectrum of a dilute solution of POPOP,\* a popular scintillator developed by F. N. Hayes and associates at Los Alamos Scientific Laboratory.

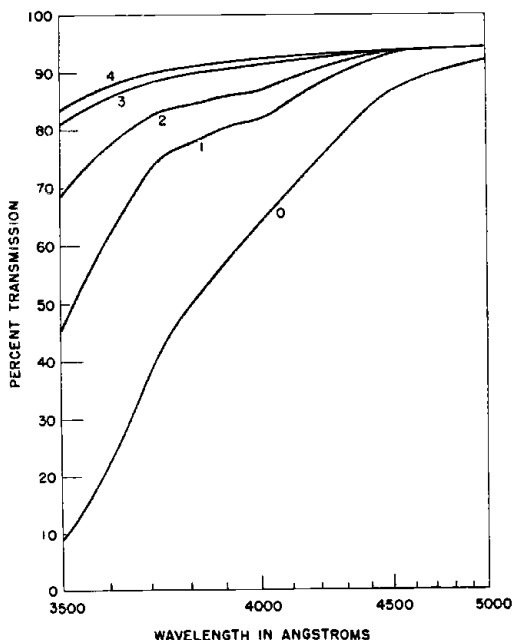


Fig. 2. Spectra showing the effect of purification of a scintillation solvent by successive vacuum distillations. Numbers on the curves refer to the number of distillations

In more concentrated solutions, the part of the emission spectrum which overlaps the absorption spectrum will be missing as a result of reabsorption. However, not all the light which is reabsorbed is lost. In most cases, the absorbing molecule is merely raised to the same excited state which produced the original photon, and a secondary photon is subsequently emitted. For example, if the molecular fluorescence yield is 98%, and 80% of the emitted radiation is reabsorbed, then after all absorptions and emissions have been completed, 91% of the original number of photons will escape the scintillator.

Light absorption by impurities is a different matter. Most impurities are nonfluorescent, so that the absorbed light is lost. Impurities are most frequently introduced with the solvent, because it is present in the largest

\* POPOP = 2, 2'-*p*-phenylene-bis-(5-phenyloxazole).

concentration. For example, Fig. 2 shows the transmission spectrum observed for a particular scintillation solvent after each of several successive vacuum distillations. The precautions which must be taken to remove absorbing impurities become greater in proportion to the size of the scintillator. In a scintillator of small volume, such as is used for counting an internal sample, purification of the solvent is not a particularly difficult problem. On the other hand, counters of large volume present considerable difficulties with respect to purification of the solvent.

Another impediment to getting the light out of the scintillator is the reflection which may occur at the surface. If light which is initially directed toward the photocathode is reflected away, this adds to the difficulty of getting the light out of the scintillator and on to the photocathode. Reflection at the interface between the scintillator and the phototube may be almost completely eliminated if we make optical contact between the scintillator and the photocathode. In using phototubes in which the cathode is deposited on the inside surface of the window, this is usually accomplished by filling the space between the scintillator and the window with a transparent fluid such as glycerin, mineral oil, or silicone\* fluid. However, in many experiments using the internal-sample technique it is inconvenient to make optical contact. Therefore, it is instructive to consider the problems which arise when optical contact is not used.

There are two cases of reflection which must be considered. The first case occurs when the light makes a small angle of incidence with the interface between the scintillator and air. A small fraction ( $\sim 5\%$ ) of the light is reflected. This is often referred to as Fresnel reflection. As the angle of incidence increases, the reflectivity increases gradually at first and then rises rapidly toward  $100\%$  as the critical angle is approached. Beyond the critical angle the incident light is totally reflected. The subsequent history of the reflected rays depends upon the shape of the scintillator and its index of refraction. The phenomena which occur may be illustrated if we assume that the scintillator has the shape of a rectangular parallelepiped as shown in Fig. 3. We assume that the lower face of the scintillator is adjacent to the photocathode but not in optical contact with it. The other faces are backed up by an efficient reflector which is likewise not in optical contact with the scintillator. The shaded areas represent four of six cones whose apices coincide at the point of origin of a scintillation, and whose elements make the critical angle with the six faces. Rays originating within these cones escape through the respective faces with about  $95\%$  probability. This is illustrated by rays A and B in Fig. 3. But in liquid scintillators, the index of refraction is sufficiently large that part of the radiation falls outside the cones defined by

\* DC 200, manufactured by Dow-Corning Corp., Midland, Michigan is often used. A viscosity of 30,000 centistokes is suitable for temporary contacts, while  $10^6$  centistokes is preferred for permanent contacts.

the critical angle. This is illustrated by ray C in Fig. 3. It may be shown that such a ray will strike every surface beyond the critical angle, and so will be permanently trapped within the scintillator. The greater the index of refraction, the larger the fraction of the emitted light which is so trapped. Furthermore, consider the fate of rays similar to A and B which escape

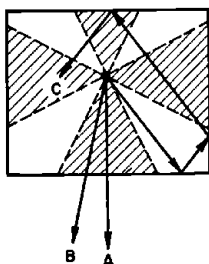


Fig. 3. Diagram illustrating light trapping in a scintillator. A and B are rays which strike a face within the critical angle. C is a ray which is trapped in the scintillator

through one of the side faces. These rays will be reflected back into the scintillator. Upon re-entering the scintillator they will necessarily be refracted within the critical angle. Again, one can show that such rays can only escape through the opposite face or through the same face, but never through any of the remaining four faces. This leads us to the surprising conclusion that a reflector around the side faces is actually useless in this case, and the only light which will ever have a chance of reaching the photocathode is that which is emitted in the two vertical cones. For an index of refraction of 1.52 (corresponding to the popular solvent toluene at a wavelength of 4300 Å), this means that only 25% of the emitted light can reach the photocathode. It may be interesting to note at this point that if two phototubes were to be employed in this case, they should be placed at right angles to each other. If they are placed on opposite sides they must share the same light, but if placed on mutually perpendicular sides each tube uses light which could not be seen by the other tube anyway, so that 50% of the emitted light could be utilized. Similarly, three tubes could utilize 75% of the light, if properly placed. Use of additional photomultipliers will not increase the light output further.

The above conclusions apply only to the hypothetical case of a rectangular parallelepiped with perfectly polished faces. For greater detail the reader is referred to the work of SHURCLIFF and JONES<sup>1</sup> and GILLETTE.<sup>2</sup> Nearly all the regular geometrical shapes show similar light trapping, however. The right circular cylinder, a convenient and frequently used shape, shows even greater light trapping than the rectangular parallelepiped. Two methods may be used to reduce these losses. The first method consists of roughening the surfaces of the scintillator. This breaks up the cyclic pattern of total reflection

and enables more of the light to escape. The second method consists of choosing a more favorable shape for the scintillator.

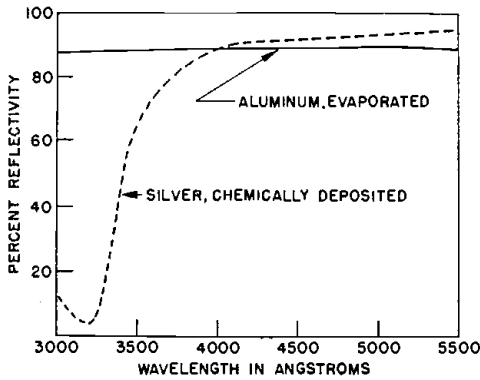


Fig. 4. Reflectivity vs. wavelength for evaporated aluminum and chemically deposited silver. (Courtesy John Strong, *Procedures in Experimental Physics*, Prentice-Hall, Inc., New York, 1938, p. 375.)

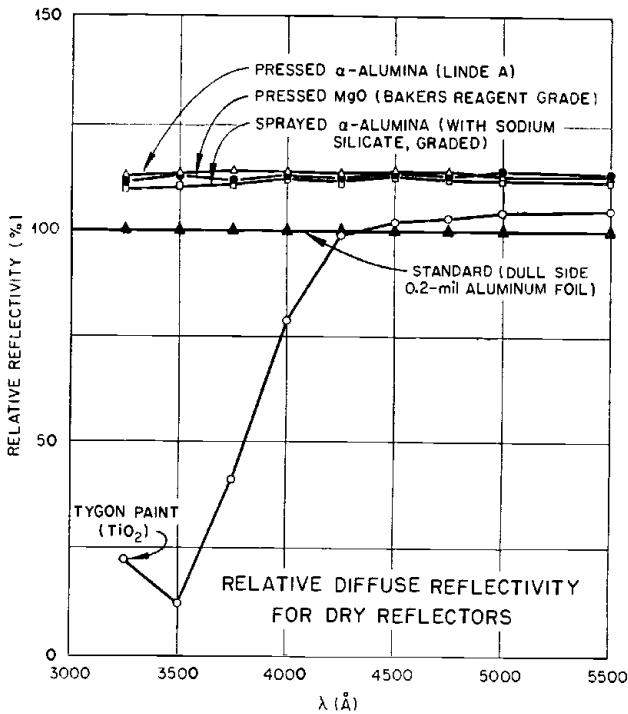


Fig. 5. Relative diffuse reflectivity for several dry reflectors. (Courtesy Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.)

It is clear from the foregoing that an efficient reflector is an important factor in the process of light gathering. When the largest cross section of the scintillator is comparable to the photocathode area, the use of focused optical systems is impractical, and we must resort to the method described above, in which one face of the scintillator is placed in contact with the phototube, and every other face is backed up by a reflector. Although metallic reflectors may be used, their chief advantage of specular reflection is lost in such a system. The best metallic reflector for scintillation work is evaporated aluminum, but it can at best provide only 90% reflectivity. With diffuse reflectors, however, reflectivities of 96% or better may be achieved. The absolute specular reflectivities of two metallic surfaces are given in Fig. 4, while total reflectivities for several diffuse reflectors are expressed relative to that for aluminum foil in Fig. 5.

Another type of reflector is sometimes useful. This makes use of the principle of total internal reflection which we discussed earlier. This type of

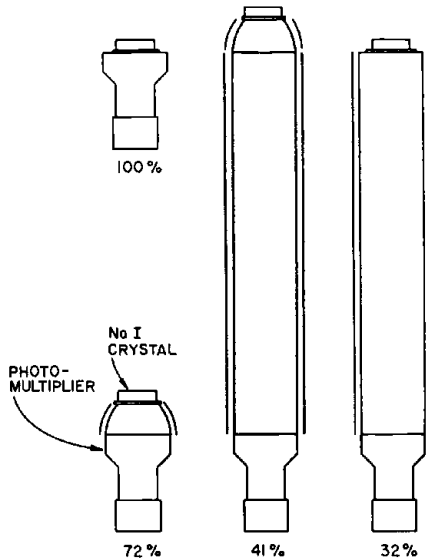


Fig. 6. Efficiency of light transmission by several arrangements of light pipers.<sup>3</sup> Long pipers shown are 3 in. in diameter by 20 in. long. Percentages given represent the relative pulse height obtained. Lines drawn outside the pipers represent bright aluminum foil.

reflector does not find any application in gathering the light from the scintillator, but may be used to transmit that light over large distances. In this application, it is referred to as a 'light piper'. Light pipers are useful when one wants to separate the phototube from the scintillator. Light pipers are usually made from a transparent plastic such as polymethylmethacrylate, but excellent pipers may be made from fused quartz. The properties of a

number of different light pipe arrangements have been given by HARRIS and BELL.<sup>3</sup> A portion of their results is reproduced in Fig. 6. It is clear that the use of any light pipe reduces the efficiency of light collection, but after a certain length is reached, the pipe may be made longer without much sacrifice of light collection. Best performance is obtained if the cross section of the scintillator is smaller than that of the pipe. In this case, a curved region in the pipe, called a 'critical-angle adapter' may be designed in such a way that all rays entering the pipe from the scintillator are totally reflected, and hence efficiently 'piped'.

Having caused a large fraction of the scintillation light to fall upon the photocathode, we meet the problem of the efficient conversion of photons into photoelectrons. The first aspect of this problem which we must consider is the wavelength dependence of the cathode photosensitivity and, in relation to it, the distribution in wavelength of the scintillation photons. These factors are illustrated in Fig. 7, which shows the quantum sensitivity spectrum of a type 6292 photomultiplier and the quantum emission spectra of some liquid

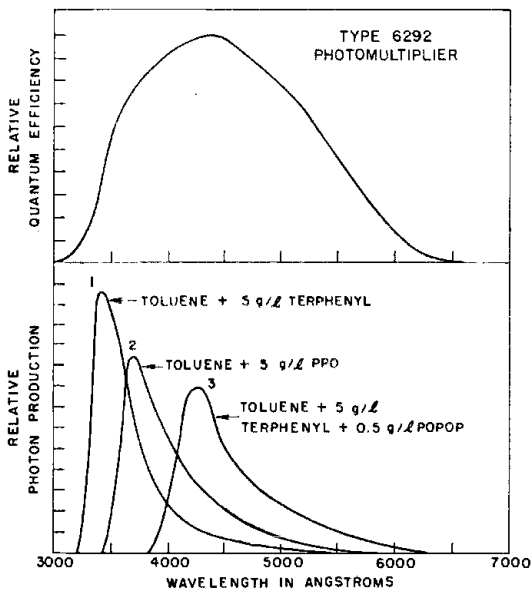


Fig. 7. A comparison of the emission spectra of three liquid scintillators with the sensitivity spectrum of a type 6292 photomultiplier.

scintillators as reported by SWANK *et al.*<sup>4</sup> The efficiency of a given combination of scintillator and photomultiplier may be expressed as an integral over the wavelength of the product of the emission and sensitivity functions. If this efficiency is normalized to unity for a hypothetical scintillator which emits all its energy at the single wavelength corresponding to maximum response

of the phototube, then the efficiencies of scintillators 1 and 3 turn out to be 50% and 87% respectively. Although the actual photon yields of the two solutions are nearly the same, the pulse heights obtained with the second solution would be much larger for the phototube in question.

A second factor which will affect the efficiency of conversion of the optical signal into an electrical signal is the optical reflectivity of the photocathode. A significant fraction of the incident photons will be reflected back into the scintillator system. Whether or not the reflected photons are returned to the cathode, a second time will depend upon the optical efficiency of the scintillator system.

There is another factor which has been given very little attention, but may be quite important. That is the dependence of the efficiency of the photocathode upon the angle of incidence. This is illustrated in the schematic representation shown in Fig. 8. The diagram is of course greatly magnified, since the thickness of the photocathode is very small. It shows typical rays

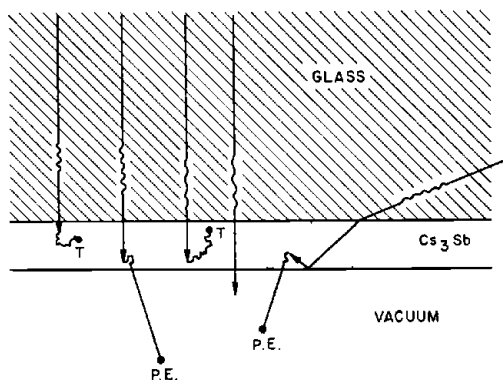


Fig. 8. Schematic diagram showing the photoelectric process in a cesium-antimony photocathode. T denotes a photoelectron which is trapped or degraded below the energy level required to escape. P.E. denotes a photoelectron which escapes into the vacuum

that one might imagine entering through the glass. Some of the rays are stopped far from the surface, and in this case there is a high probability that the photoelectron will be trapped before it reaches the surface; or it may lose so much energy that it will no longer be able to overcome the potential barrier at the surface. The thinner the photocathode, the greater will be the probability of the photoelectrons escaping through the surface. On the other hand, if the cathode is made too thin, many of the incident rays will be transmitted and so cause no photoelectric effect. So the optimum thickness occurs when the total losses are minimized. It is obvious that losses may be made smaller if the light makes a large angle with the photocathode as illustrated by the ray on the right-hand side of Fig. 8. This effect may have a

bearing on the difference in efficiency between a system using optical contact and one not using optical contact. When optical contact is made, the rays coming from the scintillator have all angles with respect to the photocathode, but when there is no optical contact, there are no rays beyond the critical angle of the glass. The effect may also have a bearing on the use of light pipes, since the geometrical arrangement usually employed greatly reduces the average angle of incidence with the photocathode.

Having considered many of the factors which relate to the efficiency of conversion of the original scintillation into a photoelectron signal, we come to the question of the over-all efficiency or conversion factor. This may be expressed as the average number of electron-volts of particle energy which must be dissipated in the scintillator in order to produce one photoelectron at the photocathode. For a particular kind of particle, this will be a figure of merit for the scintillation counter. Experimental results indicate that for a small-volume solution of 5 g/l. POPOP in air-saturated toluene, using optical contact with a type 6292 photomultiplier, and with an efficient reflector, the conversion factor is approximately 1500 eV per photoelectron. This factor serves as a basis for predicting the performance of a liquid scintillation counter.

In this discussion we are concerned with the sensitivity of the liquid scintillation counter. In order to determine this we must know what factors limit the smallest pulse which we can detect. Obviously, to be detected, a scintillation must produce at least one photoelectron. Above that, however, there are practical limitations which often prevent detection of every scintillation which produces one or more photoelectrons. The small magnitude of the pulse is not a problem. By the use of amplification by secondary emission, even a single-electron pulse may be amplified to the level needed to overcome the noise in a conventional pulse amplifier, and by further amplification in the latter may be brought up to the level necessary to operate counting circuits. The real limitation on the counting of small pulses is imposed by the presence of a large number of background pulses arising in the scintillation counter itself.

One type of background, which is particularly characteristic of this type of counter is caused by thermionic emission from the photocathode. The thermionic emission in the photomultiplier type 5819 was found by MORTON<sup>5</sup> to consist of about 5000 electrons/sec at room temperature. Thermionic emission may also occur at the dynode surfaces, but this produces smaller pulses, since fewer stages of multiplication are available.

A second important type of background in the photomultiplier is caused by positive ions. Ions may be produced in the residual gas or at the dynode surfaces as a result of bombardment by the electron avalanche. The avalanche may be caused by a previous scintillation or by a thermionic electron. The positive ion is attracted toward the cathode by the potential gradient in the

tube. If it strikes the cathode after acquiring sufficient kinetic energy, a pulse consisting of many secondary electrons may be generated. This pulse is amplified in the usual manner, producing a spurious count. If the pulse is a result of a previous scintillation, it is called an afterpulse, and appears as a secondary or satellite pulse following the initiating pulse by 1–10  $\mu$ sec. If caused by a thermionic electron, it appears to be random in time, and contributes to the general background. Since only a small number of thermionic electrons produce satellite pulses, the rate of occurrence of such pulses is much less than the rate of occurrence of thermionic electron pulses. However, since the satellite pulses are much larger than the thermionic pulses, they are an important impediment to the counting of low-energy radiations.

In addition to pulses originating within the tube, any external disturbance which creates a light flash visible to the photocathode will produce a spurious pulse. One source of background which is probably of this nature results from electrical gradients across the glass envelope of the phototube. Noise pulses arise when the tube is mounted in a grounded can with the cathode at a high negative voltage. They may be avoided by operating the cathode at ground potential, by 'floating' the tube electrically, or by 'guard-ringing' the tube envelope with an intermediate shield operated at cathode potential. Light flashes may be caused by scintillations in materials other than the liquid scintillator itself. Among the materials which scintillate to a small degree are (1) the glass envelope of the phototube, (2) plastic light pipes, (3) air, (4) insulators inside the phototube, and (5) cells used for containing the scintillator. Even if a material is an extremely poor scintillator, a small amount of light may be produced by the Čerenkov effect. Light flashes sometimes arise inside the photomultiplier, as a result of the electron avalanche. These may produce an afterpulse or, if more than one phototube is used, may cause false coincidences in two or more tubes. Since the afterpulse is delayed by the transit time of electrons in the tube, the coincidence is not perfect and may be rejected in circuits with high resolution. A source of light which is particularly troublesome in counters with high sensitivity is caused by phosphorescence. Previous exposure to daylight gives rise to long-term light emission from many transparent substances. Ordinary glasses are particular offenders. Although the phosphorescence yield is very low, the intensity of daylight is so high in comparison to the intensity obtained in a scintillation that phosphorescence may completely swamp the counter for minutes or even hours after exposure of its glass parts to daylight. This emission is continuous in nature so the pulses produced are all of single photoelectron magnitude. They are therefore almost identical in nature to the pulses caused by thermionic emission. Another possible source of photon background is chemiluminescence. Ordinary scintillating solutions do not show chemiluminescence, but it may be present when certain foreign materials

are introduced with the sample or for the purpose of increasing the solubility of the sample.

In addition to these special sources of background, one has the usual sources of background which may occur in any counting system: (1) electrical disturbances arising from poor insulation, etc., (2) vacuum tube noise in amplifier circuits, and (3) background counts from extraneous radiation which excites the scintillator itself, and is indistinguishable from the radiation from the sample. The first two of these may be made negligible by proper design. The third is dealt with in the usual manner by shielding, anticoincidence techniques, or pulse-amplitude selection. A special type of high-energy background is that from naturally-occurring isotopes which may be an integral part of the counting solution. For example, hydrocarbons synthesized from contemporary biological materials may give rise to a background of  $C^{14}$  radiations.

Of all the sources of background described above, that arising from the photomultiplier is the most troublesome. It is therefore important to express this background quantitatively. Although it may vary greatly from one tube to the next, the typical result is shown in Fig. 9. In this figure is plotted the number of counts/sec observed as a function of the setting of the pulse-height selector. All pulses larger than the threshold of the pulse-height selector are counted. In order to express the threshold of the pulse-height selector in fundamental terms, it is given in terms of 'photoelectron-heights' or simply 'electron-heights'. When the pulse-height selector is set at one 'electron-height', then the smallest acceptable pulse is equal to the average pulse height produced when one electron is liberated from the photocathode. In the discussion to follow, pulse heights will frequently be expressed in terms of electron-heights. It is to be noted, however, that a photoelectron will not always produce a pulse of one electron-height. The pulse heights from a sequence of one-electron events will be distributed statistically about the mean value of one electron-height as a result of statistical processes in electron multiplication. As shown in Fig. 9, the counting rate does not drop abruptly when the discriminator level is raised above the one-electron-height level, but falls off gradually, showing a finite counting rate even at settings of several electron-heights. However, the long tail on the curve shown in Fig. 9 is not due to single-electron events, but rather to pulses from positive ions and other causes.

Counting of high-energy radiations, such as the beta-rays from  $P^{32}$  ( $E_{\max} = 1.7$  MeV), may be readily accomplished by the simple expedient of raising the discriminator level to 20 or 30 electron-heights, thus reducing the background to negligible values while reducing the counting efficiency only slightly. With radiations of lower energy, such a clean discrimination is not possible on the basis of pulse height alone. Thus the counting of  $C^{14}$  is difficult and the counting of  $H^3$  entirely impractical by this technique.

Several techniques have been devised for the counting of small pulses. The first method which suggests itself almost immediately consists of reducing the thermionic emission by cooling the photomultiplier. The thermionic emission from the Cs-Sb photocathode decreases by a factor of 2 for every 13°C that the temperature is reduced. If the thermionic counting

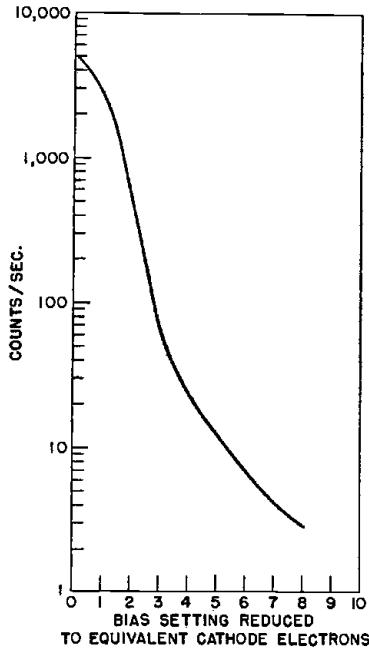


Fig. 9. Noise counting rate from a photomultiplier, type 5819 as a function of the bias setting of the integral discriminator.<sup>5</sup> The abscissa shows the discriminator level expressed in terms of equivalent photoelectrons

rate at 25°C is taken to be 5000 counts/sec (or 300,000 counts/min) then cooling the tube in dry ice may reduce the temperature to  $-75^{\circ}\text{C}$  and the counting rate to about  $300,000 \times 2^{-8} = 1170$  counts/min. This would still constitute a rather large background if all pulses were counted. Cooling the tube to  $-196^{\circ}\text{C}$  in liquid nitrogen would reduce the counting rate to  $300,000 \times 2^{-17} = 2.3$  counts/min, a reasonable value. However, aside from the obvious difficulty of maintaining the tube at this temperature while keeping the scintillator at or near room temperature, difficulties arise in the performance of the photocathode at this temperature. The Cs-Sb photosurface becomes non-conducting below about  $-173^{\circ}\text{C}$ . Photosurfaces now under development<sup>6</sup> remain conducting at much lower temperatures and in some cases provide lower thermionic emission at all temperatures. But in photomultipliers now commercially available, refrigeration alone does not

provide a practical means of eliminating all phototube background. Compromise solutions of the problem may be obtained by using refrigeration together with some other means of rejecting background.

A second method of counting small pulses in the presence of background makes use of two photomultipliers in a coincidence arrangement.<sup>7</sup> A block diagram of the circuit is shown in Fig. 10. The light from the scintillator

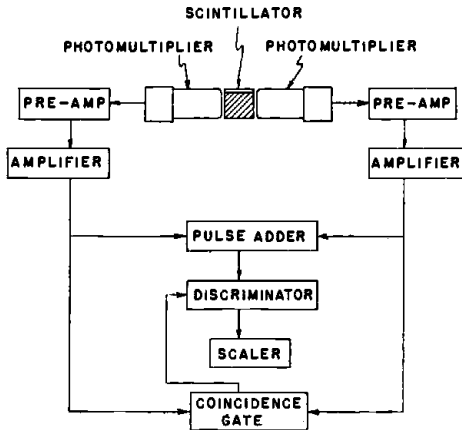


Fig. 10. Block diagram of the arrangement used for the two-tube coincidence method

is divided equally between two tubes. Since the scintillation photons are all produced in a very short time, the pulses of photoelectrons in the two tubes are essentially coincident. Background pulses arising within the tubes are independently random. In this way one may reject noise pulses even though they are larger than the scintillation pulses. The system also rejects pulses caused by phosphorescence or chemiluminescence, since these do not produce coincident pulses in the two phototubes. Many systems using this principle with or without cooling of the phototube are being successfully operated today. However, the method is not without drawbacks.

In a one-tube counter, nearly all the photons may be caused to fall on the photocathode. Hence, by dividing the light between two phototubes, we reduce the pulse amplitude in each tube to about half the pulse height of the one-tube system. Thus we may say that the efficiency for counting one-electron pulses is zero. The efficiency for counting two-electron pulses is only  $1/2$  since half of the time two electrons are produced in one tube and zero in the other. Generalizing, the efficiency for counting  $R$ -electron pulses is  $1-2^{(1-R)}$ . Thus we do not even count all the scintillations which produce two or more photoelectrons. The seriousness of this loss depends upon the distribution of pulse amplitudes.

It is instructive to calculate the resolution that is required in the coincidence circuit in order to confine chance coincidences to an acceptable level. Assuming a background counting rate of 300,000 counts/min in each tube at room temperature, one can calculate from the well-known formula that a resolving time of 5  $\mu\text{sec}$  would result in a background coincidence rate of

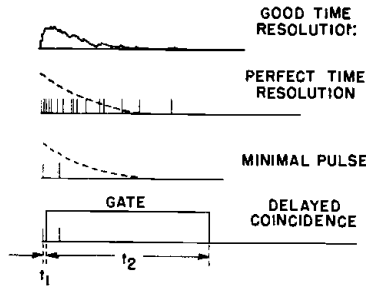


Fig. 11. Waveforms showing the principle of operation of the self-delayed coincidence method, using a single tube

15 counts/min. For some applications this would be acceptable. If, in addition, we reduced the temperature of the phototubes to  $0^{\circ}\text{C}$ , this would reduce the coincidence rate to 1 count/min, an acceptable rate for most applications. Further reduction in the resolving time is impractical, since the decay time of the scintillator is about 2  $\mu\text{sec}$ . If the resolving time were reduced to 2  $\mu\text{sec}$ , 37% of the two-electron pulses would be lost because they fell outside the resolving time. Some improvement can be achieved by selecting phototubes. Greater advances will be made when new photocathodes, now produced experimentally, are commercially available.

An alternative to the two-tube coincidence counter uses only one tube in a sort of self-delayed coincidence arrangement.<sup>8</sup> This method distinguishes scintillations from large background pulses by virtue of the fact that the scintillation pulse consists of the emission of two or more photoelectrons which are not exactly coincident in time. This circuit was originally proposed at about the same time as the two-tube circuit, but has never become popular for reasons which will become clear below. The operation of this counter can be illustrated from the waveforms shown in Fig. 11. The top waveform in Fig. 11 shows how a scintillation pulse would look when displayed on an oscilloscope having rather good time resolution. Below that is shown the waveform for perfect time resolution. The individual photoelectrons are seen. Their distribution in time follows the exponential function shown in the dashed curve. The third line shows the waveform for a two-electron pulse. Let the first photoelectron be emitted at  $t = 0$ . If we now employ a circuit

which will open a gate at  $t = t_1$  and close it at  $t = t_1 + t_2$ , then the chance that the second electron will fall within the gate is

$$p = \frac{1}{\tau} \int_{t_1}^{t_1 + t_2} e^{-t/\tau} dt, \quad (1)$$

where  $\tau$  is the decay time of the scintillator. By making  $t_1 \ll \tau \ll t_2$ , the efficiency for detecting the second photoelectron can be made to approach 100%. In particular if  $t_1 = 0.1\tau$  and  $t_2 = 2.2\tau$  the efficiency becomes 80%. (10% of the pulses occur at  $0 < t < t_1$  and 10% at  $t_2 < t$ .) If we relax our requirements to permit the same schedule of efficiencies as we obtain with the two-tube circuit, we can make  $t_1 = 0.3\tau$  and  $t_2 = 1.4\tau$ . If we set  $t_2 = 5 \mu\text{msec}$  to get 15 counts/min background as before, we find that  $\tau = 3.6 \mu\text{msec}$  and  $t_1 = 1.1 \mu\text{msec}$ . Liquid scintillators with the above decay time are available, but the time resolution required for  $t_1$  is just beyond the capability of photomultipliers which now are available. One could still use the system by lengthening all the times by a constant factor, but liquid scintillators with decay times in excess of  $4 \mu\text{msec}$  appear to suffer from excessive quenching by air. As photomultipliers and fast circuit techniques are improved, this method may become more practicable.

The foregoing three methods of dealing with background pulses from the photomultiplier are the ones which have received the most consideration. In particular, a combination of cooling and two-tube coincidence counting has been the most successfully applied technique. In order to draw a final comparison, it will be interesting to compute the efficiency which one would expect from each type of system in counting the beta-rays from tritium. This nuclide presents the greatest challenge of all the commonly-used radioisotopes. The spectrum of tritium is an allowed spectrum with an end point of approximately 18 keV. The end point corresponds to a pulse of 12 photoelectrons from the photocathode if we accept the value of 1500 eV per photoelectron. Using this value we can construct a distribution of expected numbers of photoelectrons. However, each expected number produces a Poisson distribution of actual values. Applying the Poisson distribution to each expected number, one obtains a new and somewhat broader distribution which should correspond very closely to the actual distribution of pulse amplitudes. We may then apply the efficiency schedule characteristic of each type of counter and obtain the over-all efficiency. It is assumed in all cases that the maximum theoretical efficiency is obtained.

For a one-tube system which counts every pulse of one photoelectron or greater—a condition which might be realized by suitable refrigeration—a counting efficiency of 84% could be obtained. If no one-electron pulses are counted, but two-electron pulses are counted with 100% efficiency, the counting efficiency is 68%. If one used a one-tube coincidence circuit with a

gate which accepts 80% of the two-electron pulses, the efficiency is 65%. Finally, for the two-tube coincidence circuit the efficiency will be 56%. These calculations neglect the fluctuations in pulse amplitude which may result from amplifying by secondary emission.

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**PART II**  
**INSTRUMENTATION**

