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STILBENE SPECTROMETER FOR NEUTRONS AND GAMMAS:
ELECTRONICS AND RELATED PERFORMANCE

by

Konrad Frank

September 1966

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U. S. ARMY MATERIEL COMMAND
BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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STILBENE SPECTROMETER FOR NEUTRONS AND GAMMAS:
ELECTRONICS AND RELATED PERFORMANCE

Konrad Frank

Terminal Ballistics Laboratory

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ABERDEEN PROVING GROUND, MARYLAND

FOREWORD

This work was performed as part of the instrumentation development for project HENRE (BRENN II). It is nearly impossible to single out all contributions leading to the successful completion of the spectrometer system.

The temperature dependence data constitute preliminary results of a thorough investigation performed by J. Dante (BRL) who also assisted in various special tests on the final system. The pulse-height relations and the resolution of the spectrometer system were obtained from calibration data through J. A. Devanney (BRL). The dedicated efforts of Mr. C. Roop (BRL) made the construction and testing possible in the limited time available for the development of the spectrometer system. Messrs. C. W. Williams and R. J. Scroggs, both with Oak Ridge Technical Enterprises Corporation, clarified many problems in stimulating discussions.

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B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

REPORT NO. 1335

KFrank/mba
Aberdeen Proving Ground, Md.
September 1966

STILBENE SPECTROMETER FOR NEUTRONS AND GAMMAS:
ELECTRONICS AND RELATED PERFORMANCE

ABSTRACT

The instrumentation package of a spectrometer system for neutrons and gamma rays is discussed in detail. The pulse signals produced in stilbene crystal by neutrons and gamma rays are stored simultaneously in different memory subgroups of a multichannel analyzer by using pulse shape discrimination techniques. Neutrons in the energy range from 0.5 MeV to 20 MeV and gamma rays in the energy range from 0.15 MeV to 11 MeV are analyzed with a discrimination ratio exceeding 1000:1. The lower energy discrimination limit of the system is 22 keV electron energy which corresponds to 270 keV neutron energy and 90 keV gamma ray energy.

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1. INTRODUCTION

The problem of measuring the spectra of several types of radiation in a mixed radiation field is frequently encountered in nuclear measurements. This problem becomes increasingly important in neutron studies. Gamma rays are usually associated with the generation of neutrons and their interaction with matter. For example, in radiological shielding, the radiation which has penetrated through the shield is composed of both neutrons and gamma rays. For a complete understanding of the shielding problem it is therefore essential to know the neutron and gamma ray intensities and spectral distributions both incident upon the shield and/inside the shielding enclosure. A detector system is therefore required which will enable the experimenter to measure both components of the radiation field independent of each other. When only neutrons are of interest, the problem can be solved to some extent by selecting detector systems which are virtually insensitive to gammas. On the other hand, it is nearly impossible to find detectors which exhibit the reverse characteristics, i.e., gamma detectors insensitive to neutrons.

Detector systems, sensitive to both neutrons and gamma rays, are now available which permit discrimination between types of the incident radiation based on some unique signal characteristic associated with the type of radiation incident on the detector only. A detector system based on these properties and analyzing simultaneously both neutrons and gammas in a mixed radiation field is described in this report. It is based on scintillators generating signals of different pulse shape depending only on the type of the radiation incident on the detector.

The light output of most scintillators can be described by the following expression:

$$\begin{aligned} t < 0: \ell(t) &\equiv 0 \\ t \geq 0: \ell(t) &= \sum_j L_j \cdot \exp(-t/\tau_j) \end{aligned} \quad (1)$$

$\ell(t)$: time dependent light output of the scintillator

L_j : initial magnitude of the individual components

τ_j : decaytime of the individual components.

Since the output current of the photomultiplier is proportional to the light incident on the photocathode, the same expression holds for the output current of the photomultiplier:

$$\begin{aligned} t < 0: i(t) &\equiv 0 \\ t \geq 0: i(t) &= \sum_j I_{j \text{ max}} \cdot \exp(-t/\tau_j) \end{aligned} \quad (2)$$

$i(t)$: time dependent current output of the photomultiplier

$I_{j \text{ max}}, \tau_j$: initial magnitudes and decaytimes of the individual current components.

The relative ratios of I_j and the decay constants τ_j depend on the nature of the exiting particle and are nearly independent of energy.

A particle of energy E_1 striking the scintillator will transfer a mean energy E_2 to the scintillator ($E_2 \leq E_1$). The total charge contained in the current pulse described by Equation (2) is proportional to E_2 (Reference 1* which also describes all other fundamental relationships of a scintillation counter).

* References may be found on page 107.

To obtain a voltage signal proportional to the energy (E_2) suitable for pulse height analysis, a charge to voltage conversion is necessary. This is accomplished by using a charge-sensitive preamplifier or by integrating the photomultiplier current on a RC-combination with a time constant $T = RC$. Since the signal processing system is linear the individual components can be treated separately:

$$i_j(t) = I_{j \text{ max}} \cdot \exp(-t/\tau_j) = \frac{Q_j}{\tau_j} \exp(-t/\tau_j) \quad (2a)$$

Q_j --- total charge contained in the j^{th} component.

Upon integration of this current ($T \gg \tau_j$) the following result is obtained:

$$e_j(t) = \frac{Q_j}{C} [1 - \exp(-t/\tau_j)] \quad (3)$$

$$E_{j \text{ max}} = \frac{Q_j}{C} \quad (3a)$$

$$E_{\text{max}} = \frac{1}{C} \sum_j Q_j = \frac{Q}{C} \quad (3b)$$

$$Q = \sum_j Q_j \text{ ---total charge of the pulse} \quad (3c)$$

E_{max} represents the energy information extracted from the signal. For discrimination among 2 or more kinds of radiation additional information contained in the shape of the scintillation signal (Q_j/Q , τ_j) is required. Ideally the shape information should be independent of energy. This is the case for most scintillators over a wide energy range.

Usually it is sufficient to describe the scintillation decay by only two components (fast and slow component):

$$i(t) = A \cdot \exp(-t/\tau_1) + B \cdot \exp(-t/\tau_2) \quad (4)$$

Based on this simple model, various scintillation materials have been investigated in the past to determine experimentally the characteristic parameters A , B , τ_1 , and τ_2 which are dependent on the type of incident radiation. Some of the results for stilbene are found in References 2, 3, 4 and 5 (Appendix 1). The agreement among the data is not good because the scintillation decay of stilbene cannot be accurately described by two exponentials. Bollinger and Thomas (Ref. 4), in fact, reach the conclusion that "It does not seem useful to describe the stilbene decay curves in terms of exponential components." From the work of Walter and Coche (Ref. 5) it can be seen that the "nonlinear exponential decay" of stilbene is better approximated by assuming two exponentials for the slow component:

$$B_1 \geq 0.9B, \tau_{21} = 400 \text{ nsec}$$

$$B_2 \leq 0.1B, \tau_{22} = 2000 \text{ nsec}$$

In spite of this complex behavior stilbene and some liquid scintillators are best suited for extracting pulse shape information since they exhibit the fastest initial decay τ_1 (Ref. 7, 8, 9). Stilbene was finally chosen for its superior performance for gamma rays.

Many experimental techniques have been developed to perform the discrimination among kinds of radiation. Early techniques were based on the ill-defined, non-linear saturation properties in the last few stages of a photomultiplier tube. (Ref. 10, Survey of PSD Techniques). These techniques afforded the selection of one type of radiation and rejection of a second type

(usually selection of neutrons with gamma rejection) and suffered severely because of count-rate limitations, critical adjustment and limited energy range.

With the introduction of the zero-crossover timing concept (Ref. 11) the above limitations were gradually removed. Pulse shape information is extracted by using the time difference between the start and the zero-crossing of the differentiated energy pulse. Examples of these efforts are given in the cited references (Ref. 12 - 20). These techniques were used with practically all scintillators for discrimination between the basic interaction particles. The interaction of system parameters was investigated analytically and optimized for special cases (Ref. 19, 20).

The instrumentation system described in this report was designed with the purpose of direct control of the parameters over a wide range and clear separation of the signal processing functions and can therefore be used with any detector exhibiting pulse-shape differences.

2. THEORY AND DESCRIPTION OF THE BASIC PULSE SHAPE DISCRIMINATION SYSTEM

The basic function of the pulse shape discrimination system is explained by the simplified block-diagram, Figure 1. It consists of the detector-preamplifier, the energy processing channel, and the time processing channel. The current output of the detector-scintillator and photomultiplier is integrated by the RC-combination of time constant $T = RC$ to obtain a charge-proportional voltage pulse.

After passing through the time pickoff device the pulse enters the main shaping amplifier which performs the following operations:

- (a) RC - integration with a time constant T_i ;

(b) One differentiation with a RC-network or delay-line, output - voltage e_1 ;

(c) A second differentiation of the same type, output voltage e_2 .

The amplifier also furnishes the necessary gain to obtain an output voltage for pulse height analysis.

The signal pulse is then stored in a delay-line. This delay provides time for performing the necessary operations in the time processing channel. From this analog storage the pulse enters a linear gate which is operated by the output of the time-processing channel and is open only for pulses which satisfy requirements established in that channel. The output of the linear gate is therefore the shape-discriminated energy information.

The operation required of the time processing channel consist of measuring the time-difference between the start of the signal pulse and the time that signal crosses the zero-level after it was operated on by the shaping amplifier. As will be shown next, this time difference is in the ideal case dependent only on the shape of the signal. The time channel also selects one time difference associated with one kind of particle striking the scintillator and operates the linear gate. This is accomplished in the following manner:

The signal pulse passing through the time pickoff generates the start pulse which is used as a timing pulse for all subsequent operations. The start of this logic pulse coincides in the ideal case with the beginning of the signal pulse ($t_1 = 0$). This pulse starts the time-to-pulse-height converter (TPHC).

A zero-crossing detector which produces a logic pulse (stop pulse) at the time $t = t_0$ when the shaped energy signal goes through zero, stops the time to pulse height conversion process. The output voltage of the TPHC is therefore proportional to the time difference between the reference time t_1 and the zero crossing time (t_0) and contains all the information available on the shape of the signal. This voltage is analyzed by a single channel analyzer (SCA) which is set from a logic zero to a logic one if the voltage is within the limits established by the SCA window. The start pulse also passes through a delay-line of the same amount of delay as used in the analog storage module and is then used as a strobe pulse to read out the single channel analyser. Therefore the analog energy signal and the logic gate signal both appear at the proper moment at the linear gate. This allows the identified energy signal to pass through the gate for further analysis.

The relations between pulse shape and zero crossing time are illustrated in Figure 2. Following simplifications are used:

- (a) $T \rightarrow \infty$
- (b) $T_i \rightarrow 0$
- (c) $Td_1 = Td_2 \gg \tau_{j \text{ max}}$, delay line differentiation
- (d) Two decay times τ_1 and τ_2 .

For the charge-proportional output following relations are obtained from Equation 3:

$$\begin{aligned}
 e(t) &= \sum_1^2 \frac{Q_j}{C} [1 - \exp(-t/\tau_j)] = \\
 &= \frac{Q}{C} [1 - \rho_1 \exp(-t/\tau_1) - \rho_2 \exp(t/\tau_2)] \quad] \quad (5) \\
 Q &= Q_1 + Q_2 \text{ ---total charge} \\
 \rho_1 &= \frac{Q_1}{Q}, \quad \rho_2 = \frac{Q_2}{Q} \text{ ---individual charge ratios}
 \end{aligned}$$

The signal formed by double delayline differentiation has the following form
(For more detail see Appendix 3):

$$e_2(t) = U(t) \cdot e(t) - 2 U(t - T_d) \cdot e(t - T_d) + U(t - 2T_d) \cdot e(t - 2T_d) \quad (6)$$

where $U(t)$ is the unit step function.

For the particular case chosen ($T_d \gg \tau_2$) the signal $e_2(t)$ will cross zero the same amount of time after the time T_d , as it needed to reach one-half of the maximum voltage beginning at zero time. For the case of only one component of the scintillation decay the following zero crossing time is obtained (See Appendix 3):

$$t_o = T_d + \tau \cdot \ln 2 \quad (7)$$

If the zero crossing time for the fast component is t_{o1} ($Q_2 = 0, Q = Q_1$) and that for the slow component is t_{o2} ($Q_1 = 0, Q = Q_2$), then the zero crossing time for a pulse consisting of both components will cross at a time $t_{o1} < t_o < t_{o2}$. This time is dependent only on the ratios of the individual components and their decay times and therefore depends only on the nature of the exciting particle.

To obtain simultaneously the energy distribution of two or more kinds of radiation the following modifications of the basic pulse shape discrimination system are possible:

(a) The energy signal from the analog storage enters the desired number of linear gates which in turn are operated by the same number of single channel analyzers selecting different portions of the time to pulse

height converter output voltage. Each linear gate feeds one multichannel analyzer.

(b) The appropriate number of single channel analyzers operate through a logic "OR" circuit on only one linear gate which feeds only one pulse height analyzer. The gate signals produced by the individual single channel analyzers select memory subgroups of the multi-channel analyser. The energy spectrum of each kind of radiation is stored in a different memory subgroup.

(c) A two-parameter multichannel analyser is used to record the energy and timing information simultaneously.

This third method is preferable since it offers more insight into the pulse shape discrimination process and permits better classification of the discriminated energy output by simple treatment of the recorded data than any of the other two. However, since multichannel analysers with gating of 4 memory subgroups were already available, the second option was chosen. In the following section this system is described in more detail.

3. CONSTRUCTION, DESCRIPTION AND PERFORMANCE OF SYSTEM MODULES

Except for the preamplifier-photomultiplier assembly and the interface units, all equipment was constructed following the recommendations of AEC-TID 20893 and is therefore compatible with many commercially available components conforming to the same standards. The design started in late 1964 and only those modules not available commercially with the necessary performance were designed and built in-house. All equipment was transistorised and whenever possible, silicon semiconductors, computer grade capacitors and printed circuits were used. High stability metal-film

resistors were used whenever the requirement arose. Supply voltages were standardized at $\pm 24\text{V}$ and $\pm 12\text{V}$. The analog signal range is 0 to 10V positive. Two types logic pulses were used:

Very fast: 12 mA negative, 20 nsec nominal duration

Fast : 4V positive, 0.5 μsec nominal duration.

Two impedance levels were used for all signal lines, 50 and 93 ohms. The coaxial cable is of the double shielded type, RG 223/U for 50 ohm and RG 71B/U for 93 ohm.

In spite of the relatively long cable length between the preamplifiers and the signal processing station (up to 1500 feet) none of the anticipated problems due to signal degradation (Ref. 21) materialized and specially developed passive rise time equalizers needed not to be used.

3.1 Photomultiplier and Preamplifier:

The scintillator-photomultiplier tube was delivered as a complete package by Harshaw (Type 6S6/E-X Serial Numbers CA941 and up) and consisted of a stilbene crystal (1.5 c 1.5 inches), with light reflecting MgO coating, mounted on a 14-stage photomultiplier tube (Amperex/Philips Type 56AVP). The usual shielding arrangements against external magnetic fields were used. The photomultiplier tube was selected for its excellent rise-time (2 nsec) and small transit-time differences (less than 0.5 nsec). Two voltage divider types are recommended by the manufacturer for this tube, the A-distribution for high gain and the B-distribution for high linearity at high anode currents (Ref. 1, 22). Recent investigations by Belletini et al (Ref. 23, 24) have shown that especially the A-distribution can be improved considerably, resulting in even better overall performance in regard to linearity and maximum

attainable gain.

The voltage distribution chosen here is a further modification of Belletini's "mean optimized A-distribution" and is shown in Figure 3 with electrode voltages and voltage differences at the maximum supply voltage. By using positive high voltage the cathode-section is kept close to ground potential to prevent spurious signals from possible electrostatic discharges.

Since the gain change of a photomultiplier with this type of simple voltage divider is directly proportional to the ratio of the average anode current to the bias network current, the latter was chosen relatively high. The output section of the bias network was designed for use with a large variety of circuits. Signals can be tapped off beginning at dynode 12. The voltage between the last dynode (D14) can be varied by plugging in different resistor values for special applications. The complete divider circuit is mounted on a printed circuit board (P.B. 56AVP) directly on the base of the photomultiplier tube. The two adjustments, G1 and G2, are set according to the manufacturers data: G2 controls the collection of the photoelectrons by the multiplier structure while G1, in effect, controls the active cathode area, again for special applications.

The photomultiplier base and voltage divider board are mounted in a shielded case which also contains the preamplifier and necessary connectors. The preamplifier can be used in following modes: inverting, non-inverting, and charge sensitive. Figures 4 and 5 show the two versions of the complete detector assembly which were used. In the first case the signal is taken from the anode, in the second case from one of the dynodes. In both versions the preamplifier is used only for the charge proportional signal and mainly

for the purpose of matching the outgoing signal line as perfectly as possible on the sending end. This is very important since the receiving end is mismatched by the inductance of the time pickoff unit and part of the pulse is reflected back to the preamplifier. If this reflection is not completely absorbed it will reach the time pickoff-unit again and cause timing errors.

The charge-to-voltage conversion is performed by the usual RC-integration. Because of the high gain of the photomultiplier a large and well defined integrating capacity of 200 pF can be used and high stability is thereby obtained. The selection of the integrating time constant is important since it represents the first "collection time." It should be long enough so that the slow components of the scintillation decay can make a significant contribution to the pulse obtained. On the other hand this time constant should be short enough to prevent pulse pile-up. Furthermore it affects the signal-to-noise ratio (Ref. 1). The best signal-to-noise ratio is obtained for an integration time constant equal to the scintillation decay time constant. This value is not an optimum value for pulse shape discrimination purposes. A time constant of 2 μ sec was finally chosen (See Appendix 1).

The preamplifier is a high performance operational amplifier with differential input and DC coupling. The schematic is shown in Figure 6. The circuit uses a long-tail amplifier pair (Q_1 , Q_2) followed by an emitter follower stage (Q_3). The diodes between the inputs (D_1 , D_2) make quick recovery after overload possible, while D_3 is a zener diode used for DC-level shifting. Bootstrapping is used (electrolytic capacitor from emitter of Q_3 to collector resistor of Q_2) to increase the open loop gain by a factor

of approximately 20. This increase is achieved at the expense of increased open loop output impedance. The RC networks between the bases of Q_1 and Q_2 ($470 \text{ pF} - R_b$) and from collector of Q_2 to ground ($24 \text{ pF} - R_c$) are used to correct the open loop frequency response to assure stability under certain feedback conditions. Precision resistors R_1 and R_2 , and in the differential mode R_3 and R_4 in addition, determine the closed loop gain. C_T serves either in conjunction with C_2 as feedback capacitor in the charge sensitive mode, or, as shown in Figures 4 and 5, as a trimmer capacitor across one of the feedback resistors to correct the pulse shape. This is especially necessary in the arrangement shown in Figure 4, where large feedback resistors are used.

Experimentally the following results were obtained when driving a cable of 93Ω impedance terminated at both ends:

Risetime:	less than 30 nsec
Range:	0 to + 1.5V
Linearity:	better than 0.2%.

Only one-half of the output voltage is available across the receiving-end termination. If the indicated range is exceeded, the risetime ($30 \leq 32 \text{ nsec}$ for 0 to + 1.5V) increases as much as 10 nsec at 3V output voltage while the linearity remains the same. Therefore, the output range of the preamplifier is restricted to 0 to 1.5V for applications requiring pulse shape discrimination. The R-C networks ($75 \text{ pF} - 100 \text{ ohm}$) across the output of the preamplifier (Figures 4 and 5) are used to compensate for the inductive component of the output impedance. The sending-end termination is adjusted for minimum reflections when driving the preamplifier output by a sweep

generator through 500 feet of 93 ohm cable over the frequency range of 0 to 30 MHz.

In Figure 7 the dependence of the conversion gain of the complete detector assembly on high voltage is shown. Two limits are indicated in Figure 7: maximum delivered preamplifier voltage (750 mV) and the minimum high voltage (1860V) which results from the minimum specified voltage of 80V between the dynodes of the photomultiplier. With lower supply voltage (down to 1400V) the operation of the photomultiplier is still satisfactory in every respect except for count-rate-dependent gain shift. As an example, for a supply voltage of 1600V, the gain increases for count-rates below 1000 counts per second. An increase of approximately 20 percent is observed for count rates of 100 counts per second.

The count rate dependence was examined using a 0.5mCi Cobalt-60 gamma source and the arrangement as shown in Figure 4, driving the low level input of a RCL Model 21105 Analog to Digital Converter (ADC) in a RCL Model 20624 multichannel analyzer through an inverting amplifier ($\Omega 01/20$). No count-rate-dependent gain shift of greater than 1 percent (± 1 channel, Compton edge of Co-60 in channel 100) attributable to the photomultiplier was found up to a count rate of 120,000 counts per second. This count rate, exceeding the specification limits of the Model 21105 ADC by a factor of 2, was the highest count rate used in this test.

The following calculations demonstrate the negligible contribution of the voltage divider network to gain shift:

The pulse obtained from stilbene is approximated by a single exponential of about 30 nsec decay. The following results are then obtained:

charge/pulse: $Q = i_{a \text{ max}} \cdot \tau = 30 \cdot 10^{-9} \cdot i_{a \text{ max}}$
(Coulombs, Amperes)

charge proportional output voltage, $C = 200 \text{ pF}$:

$$e_{\text{max}} = \frac{Q}{C} = 1.5 \cdot 10^2 \cdot i_{a \text{ max}}$$

(Volts, Amperes)

For $i_{a \text{ max}} = 10 \text{ mA}$, an output voltage of 1.5V is obtained.

The average anode current (I_A) depending on count rate ($N = 10^5$ counts per second) is therefore

$$J_A = N \cdot Q = 10^5 \cdot 30 \cdot 10^{-11} = 30 \text{ } \mu\text{A}$$

assuming all counts are associated with the maximum peak current of 10 mA.

The gain shift due to this average anode current is proportional to the ratio of this current to the divider network current (J_B , Ref. 1):

$$\frac{\Delta G}{G} \div \frac{J_A}{J_B} = \frac{30 \cdot 10^{-6}}{4 \cdot 10^{-3}} = 7.5 \cdot 10^{-3} = 0.75\%.$$

After initial application of the high voltage the gain usually increases by about 10 percent in the course of 4 hours and remains stable within 1 percent after this time. Calibration is achieved by high voltage changes which are also used to correct for long-term gain shifts.

The temperature dependence of the complete detector assembly (scintillator - photomultiplier - preamplifier) was investigated over the range of 0 - 55°C. It was found that the gain changes about 1 percent over this temperature range, decreasing with increasing temperature. Above 55°C the gain decreases sharply. Previous investigations on the temperature dependence

of stilbene (Ref. 25) show a temperature coefficient of -0.23 percent per degree Centigrade at 15 degree Centigrade and -0.1 percent per degree Centigrade at 40 degree Centigrade. From Figure 5 in Reference 6 a temperature coefficient of -0.25 percent per degree Centigrade can be found for both the slow and fast components in the temperature range above -50 degree Centigrade. Therefore, the pulse shape is expected to be nearly independent of temperature. The temperature sensitivity of the type of photomultiplier used is as follows (Ref. 26):

Dynodes:	None
Photocathode:	+ 1%/°C in the red region + 0.3%/°C in the green region.

Since stilbene emits most of its light in the short wavelength region of the light spectrum, a nearly perfect temperature compensation can be expected, and was experimentally observed ($\sim$ -0.02 percent per degree Centigrade, Ref. 27).

The pulse shapes of the anode and dynode currents of the photomultiplier - scintillator assembly (arrangement as in Figure 5) were carefully examined with Co-60 gamma excitation by means of a fast oscilloscope (Tektronix Type 519, risetime 0.25 nsec). Contrary to the findings of Bonitz et al (Ref. 28) no evidence of prepulses could be found in any of the samples examined. The highest supply voltage for this particular test was 3200V. This negative but satisfying result cannot be entirely explained by the different voltage distribution used, since Bonitz et al claim that the undesired prepulses they observed in the 56AVP photomultiplier originate in the focussing system of the tube.

The following output pulse shape was experimentally observed:

- (a) Risetime: 2.5 nsec, essentially that of the photomultiplier.
- (b) Pulse duration between 50 percent points: 22.5 nsec. This corresponds formally to a decay time constant of 33 nsec.

(c) No accurate values of the slower components could be obtained using this technique.

The figure for the pulse duration is in good agreement with data obtained by R. B. Owen (see Figure 5 of Ref. 29).

3.2 Energy Processing Channel.

The energy processing channel consists of the following modules connected in series:

3.2.1 Mixing Amplifier, BRL 400 MA. This module is actually a summing amplifier developed for use with solid state spectrometers. The schematic is shown in Figure 8. In this discrimination system it is used only for the purpose of impedance matching ($Z_{in} > 3k\Omega$), for providing smaller calibrated gain steps ($\sqrt{2}$ instead of the 1-2-5 sequence of the following amplifier), and for removing large common mode voltages on the signal line (differential input).

It uses two operational amplifiers similar to the type $\Omega 01XL$ and its characteristics of interest for the application at hand are as follows:

Input impedance: $3 k\Omega - 4 k\Omega$

Output impedance: 92Ω

Gain: 0, $1/4$ to $4\sqrt{2}$ in steps of $\sqrt{2}$; 75% - 100% continuous adjustment

Risetime: 20 nsec at a gain of $1/4$ increasing to 50 nsec at maximum gain

Delay: 40 nsec

Linear Range ($\leq 0.2\%$, driving a 93Ω load): 0 - + IV for minimum gain increasing to 0-2.5V at maximum gain.

3.2.2 Shaping Amplifier. This amplifier, ORTEC Model 410, is based on the design by Goulding and Landis (Ref.30). In this application it is used in the double delayline mode (800 nsec delaylines). The description and the circuits of some of the modules below can also be found in Reference 30.

3.2.3 Analog Storage. For this function the ORTEC Model 415, Sum-Delay Amplifier with a 2 μ sec delay line was selected. The module has a gain of 1 and a linear range of 0 - 10V.

3.2.4 Linear Gate. To prevent rate-dependent zero shift associated with AC-coupling, an ORTEC Model 409 was modified for DC-coupled output. The modified module has a gain of 1 and a 93 ohm source impedance. Since the following signal path to the analog to digital converter is DC-coupled and the Linear Gate module shows a typical DC-offset of about +0.3V, the zero of the multichannel analyzer must be adjusted with all Linear Gate modules connected to the 4-input selector unit (see Section 3.4, following). No zero shift greater than 1 percent total was experienced over the period of 3 months (+ 0.5 channel out of 27).

3.2.5 Pulse Stretcher, ORTEC Model 411. It is desirable to stretch the analog pulses before analyzing for pulse height to improve linearity. However, the ORTEC Model 411 pulse stretcher is not easily modified to obtain a DC-coupled output. For this reason, and because no serious nonlinearities were observed by using the short pulses from the output of the linear gate for pulse height analysis, (see Section 3.4) the stretcher was used only for the monitoring system ("Twinkle Box", see Section 3.5).

3.3 Time Processing Channel.

The purpose of the time processing channel is to measure the time-difference between the beginning of the analog pulse and the time it crosses zero after being shaped in the energy processing channel, to select a certain time difference, and to generate a logic pulse which represents the information obtained on the nature of the exiting particle. These functions are performed by the following modules:

3.3.1 Time Pickoff Unit. The logic start pulse is obtained by passing the energy signal from the preamplifier through the time pickoff unit, an ORTEC Model 260 with Model 403 or 261 Control Unit. In the control module of the time pickoff unit a discrimination level is established below which no start pulses are obtained. Since the timing technique is of the "fixed threshold" type, the start pulse occurs not at the reference time $t = 0$ but at a "machine" time $t = t_1$ which is dependent both on signal amplitude and risetime (see Appendix 2). The performance was tested with pulses of 5 nsec risetime, approximating the conditions as used in the pulse shape discrimination system. The results of this test are presented in Figure 9. A system input voltage of 75 mV corresponds to an electron energy of about 1 MeV (see Section 4.1) and it can be seen that the time pickoff unit in conjunction with the preamplifier contributes less than 2 nsec timing error above 1 MeV. An additional error of 5 nsec is produced in the energy range between 0.1 and 1 MeV when using a discriminator setting of between 1.00 and

2.00. The performance can be improved considerably by using the non-integrated output from the anode or the last dynode to trigger the start pulse. This requires the use of a second signal cable from the preamplifier. Because of the problem arising from the use of two cables this method was not used.

3.3.2 Delay Module, BRL 400D. This module delays the start pulse by a fixed amount before starting the TPHC. This delay permits a higher conversion gain to be used on the TPHC resulting in a steeper output waveform which is highly desirable for subsequent shaping.

The schematic diagram of the Delay Module is shown in Figure 10. The positive logic pulse entering any of the inputs is shaped into a narrow pulse by the tunnel diode Fan-In circuit, which is shown in detail in Figure 11. This circuit also performs a logic "OR" operation on the 3 inputs required for a different application. A tunnel diode (TD-1A) with zero bias is used as a threshold trigger and remains in its "high state" for the duration of the input pulse. The fast initial change of the tunnel diode voltage is amplified by the npn transistor (2N706), shaped into a narrow pulse in its collector circuit, and inverted by the pnp transistor (2N2048) to obtain a narrow positive pulse at the output ($E_O = 5V$, duration 20 nsec) coinciding with the start of the input logic pulse. The R-C network in the emitter of the first transistor ($15\text{ K}\Omega$, C_E) can be used for establishing a dead time for the circuit without introducing timing errors. The dead time thus introduced has a value of $0.3\text{ }\mu\text{sec}$ per 1 nF of emitter capacitance (C_E) for the circuit constants chosen.

Referring back to Figure 10, the timing pulse generated by the Fan-In circuit turns on a monostable multivibrator which remains on for the desired delay time, T_D . At the end of the delay time the delay monostable multivibrator returns to its quiescent state and turns on a second monostable generator consisting of a tunnel diode biased below the peak-current value of the tunnel diode and a fixed inductance (D6,L); this generator produces the fast negative logic pulse (-0.5V, 20 ns duration) which, after passing through the emitter follower (Q5), is used to start the time-to-pulse-height converter. The complete schematic of the printed circuit board used in the delay module (Figure 10) is shown in Figure 12.

The delay time, T_D , is dependent upon the fixed values of the timing network (C_T , R_T) and a control voltage which is derived from a linear 10-turn potentiometer. The dependence of the delay time on the dial reading is shown in Figure 13. The delay function, while not exactly linear, is a well defined and stable function and as such perfectly satisfactory. A description and analysis of the circuit is given in Appendix 4.

The rate dependence, shown in Figure 14, was obtained by using a double pulse generator to investigate the circuit behavior. The recovery curves are exponential and are shown extrapolated down to an error of 1 nsec. This performance was obtained using the resistor values shown in parentheses in Figure 12. With the values of 3.9k and 820 Ω as shown in the final schematic, the values of $t = 1.75$, 2.15 and 2.95 μsec are obtained for the 1 nsec error intercept using the same delay times of 0.4, 0.8, and 1.4 μsec . The resulting recovery time constant is about 0.25 μsec , nearly independent

of the delay. This performance can be improved even further (see Appendix 4) but was not considered necessary for this application.

3.3.3 Crossover Pickoff - Zero Crossing Detector, ORTEC Model 407. This module is the ORTEC Model 407. The performance of the crossover pickoff has to be determined in conjunction with the shaping amplifier driving it. The crossover pickoff module is generally used with the ORTEC Model 410 multimode amplifier with 0.8 μ sec delay lines. ORTEC Model 221, units which are equivalent to above combination, were also used. Normally the units are adjusted for minimum timing error (walk) with no integration in the shaping amplifier and a walk of less than ± 2 nsec is obtained for 10:1 range of the amplifier output voltage (0.8 to 8V). The threshold range is approximately 20:1 (0.5V to 10V). The timing performance, typical of all units investigated using this adjustment, is shown in the top of Figure 15. All crossover times are normalized for $\Delta t = 0$ at an output voltage of 10V. It can be seen that the timing error increases rapidly with increasing integration time and severely restricts the voltage range which can be used with a minimum acceptable walk. By making a different threshold adjustment (typically 50:1) a much better performance for longer integration time constants can be obtained; this can be seen from Figure 15, bottom. This improved performance is of great importance for a wide range spectrometry system as described in this report, especially since better pulse shape discrimination is obtained with integration time constants between 0.5 and 1 μ sec (see Section 4.5).

The model 407 crossover pickoff has threshold adjustment which only incidentally affects the walk properties. By separating the

adjustments for walk and threshold even better performance can be obtained (Ref. 31).

The ORTEC Model 420 Timing Signal Channel Analyzer, which offers full energy discrimination in addition to the zero crossover timing function, can be substituted for the 407. Slightly better timing performance is obtained.

The crossover walk can be adjusted to optimum with remarkable ease by observing the "Time Spectrum" (see Section 3.4) of a continuous energy distribution (gammas incident on stilbene) and adjusting for minimum dispersion. Usually no readjustment is required over a period of several months.

3.3.4 Time-To-Pulse Height Converter and Associated Shaping Amplifier. The time-to-pulse height converter used is an ORTEC Model 405, requiring fast negative logic pulses on the start and stop inputs. Since the output pulse of the zero crossing detector is a positive logic pulse the 405 was modified as follows:

- (a) An additional connector was provided above the stop input connector.
- (b) A resistor of $510\ \Omega$ was connected between this input and the emitter of Q_5 , stop amplifier.

The minimum trigger requirements for this additional stop input are + 0.8V, minimum duration 20 nsec. No deterioration of performance could be detected when this modified stop input was used.

The output voltage of the converter is a constant ramp with a slope selected by the conversion gain for the duration of the conversion process, followed by long exponential decay with a time constant of approximately 160 μ sec. Pulse shaping is therefore required before this pulse can be analyzed at moderate to high count rates. This function is performed by a ORTEC Mode 410 multimode amplifier with 2 μ sec delay lines operating in the double delay line mode.

The time-to-pulse height converter provides, to some degree, a trade-off between linearity and count rate capability; with increasing output-rate the average DC-voltage on the conversion capacitor, C19, decreases; thereby lowering the effective decay time of the output pulse (the time necessary for that pulse to decay one full scale value) by as much as a factor of 10. The effective pulse pile-up time of the TPHC is therefore about 16 μ sec minimum. This limit can be decreased further only by decreasing the conversion gain (increasing the conversion capacitor), thereby trading resolution against count-rate capability.

The pulse pile-up time for the associated shaping amplifier is determined by the delay lines used for shaping and is 4 μ sec plus the maximum conversion time selected (0.25 μ sec), typically 4.25 μ sec total.

The average pile-up fraction c , caused by a mean count-rate N in a system with a pile-up time T can be estimated by assuming a POISSON-distribution for the random occurring pulses (Appendix 4):

$$\epsilon = 1 - P_0 \quad (8)$$

ϵ is the fraction of pulses occurring in the time interval T , while P_0 , the probability of exactly zero counts in the time interval T , is given by the following expression:

$$P_0 = \exp(-NT) \quad (9)$$

The average count rate causing 10 percent pile-up ($NT = 0.1$) is therefore:

TPHC: 6200 pulses per second

Shaping amplifier (2 μ sec): 25,000 pulses per second.

The delayed start pulse generated by the delay module (BRL 400D) also exhibits a rate dependent timing error (see Figure 14) which is transferred fully into the time spectrum. For the unimproved version of the delay module (see Section 3.3.2), and a set delay of 1100 nsec, the pile-up time causing an error of -2.5 nsec or more is 3.5 μ sec.

Both the shaping amplifier for the energy signal and the zero crossing detector contribute additional rate dependent timing errors. From all these considerations it is concluded that the maximum useful output rate of the time processing channel is about 10,000 pulses per second. By introducing a fixed dead time in the delay generator (see Section 3.3.2) the output rate of the time processing channel was decreased thus permitting operation with good performance at input rates higher than 10,000 pps.

3.3.5 Logic Storage. This function is performed by the Sum and Delay Amplifier, BRL 400 SD, which delays the start pulse, generated by the time pickoff by the same amount as used in the analog storage (2 μ sec) to produce the

strobe pulse required for the operation of the single channel analyzers. This module is of simple construction and performs more than adequately in this application (Figures 16 and 17). The input impedance is 50 Ω nominal: The overall voltage gain is greater than 2. Two identical delay lines of 500 Ω characteristic impedance ($Z_0 = 500 \Omega$) are used in series. Reflections caused by delay line imperfections are minimized by terminating the receiving end of the delay lines with a resistance of $0.82 Z_0$. The remaining reflections are less than 3 percent of the maximum amplitude. Four emitter followers provide isolated logic outputs for which the delay line reflections are removed by passing the linear signal through a reverse-biased diode (see Figure 16). The logic pulses are not regenerated and the rise time of both are linear and logic output pulses is approximately 100 nsec, as determined by the delay lines.

3.3.6 Single Channel Analyzer. This single channel analyzer (SCA), an ORTEC Model 413, operates over the range of 0 to 10V on signals supplied by the shaping amplifier associated with the time-to-pulse height converter (0 to 10V, bipolar, 2 μ sec delay line shaping). The SCA is used in the external strobe mode as required for an output pulse synchronized in time.

For two reasons, modifications of this analyzer were required:

- (a) The strobe pulse obtained from the logic storage was too slow (rise time 100 nsec) to trigger the strobing sequence in the single channel analyzer. A tunnel diode fan-in circuit of the same type used in the Delay Module 400D (Figure 11) was added to the strobe input to overcome this problem.

- b. The output voltage of the ORTEC 410/2 μ sec multimode amplifier showed delay line imperfections consisting of a 5 percent positive "bump" at the end of the flat top portion of the shaped pulse. Since the single channel analyzer is interrogated before this "bump", the upper level discriminator of the single channel analyzer may be set again by this imperfection, after the strobing sequence is completed; the result will be spurious output pulses of approximately 50 μ sec duration (decay time of the discriminators without strobing). This problem was eliminated by increasing the length of the internal reset pulse.

3.3.7 Routing Logic Module, BRL 400 RL. The need for this module arose from the special requirements of the selected recording equipment - a multi-channel analyzer with switching of memory sub-groups (see Section 2.0, option b). The module accepts three positive logic pulses (A, B, C) and performs the logic "OR" function between two (A + B) and the logic "AND" function between the same two pulses and the third pulse (A.C, B.C). It uses regenerative "current mode logic" circuitry to obtain output pulses of controlled width. The schematic diagram is shown in Figure 18. The logic circuits are triple input units of a type developed for coincidence work (Ref. 30). To perform the "OR" function between positive input pulses with a "current mode logic", npn transistors are required, while the "AND" function calls for pnp transistors, the circuits are shown in Figure 19 and Figure 20 respectively. The addition of a timing network (consisting of a capacitor from the collector of the input transistors to the base of the reference transistor and a

variable resistor to the positive supply voltage) achieves regeneration and makes pulse-width control possible in both cases. The "AND" gates have a DC-coupled output of -6V for the logic "zero" and -0.6V for the logic "one", as required by the 4-input selector unit using these signals. Emitter followers provide low-impedance outputs. Since it is impractical to terminate the DC-couple outputs (AND-gates) in a normal manner, sending-end terminations are used (100 Ω) to eliminate multiple reflections when driving signal lines longer than 10 feet.

The minimum input voltage required (module input) was + 2.8V when using a reference voltage of + 0.64V (one forward-biased Si-junction). The minimum required pulse overlap for AND-operation is approximately 2 times the risetime of the input pulses.

3.4 Complete Pulse Shape Discrimination System

The block diagram of the complete stilbene spectrometer system as intended for field use (Project HENRE) is shown in Figure 21. All components except the scintillator-photomultiplier-preamplifier and the necessary interface equipment are located in an instrument trailer. Figure 22 shows the pulse sequence of the system for a typical set of parameters. The description of the operation of the individual modules as given in previous sections make a further detailed description of the operation unnecessary. The arrangement of the modules for two pulse shape discrimination systems is shown in Figure 23.

3.5 Multichannel Analyzer.

The multichannel analyzer used was a RCL Model 20624, 512 channel analyzer with memory sub-groups of 64, 128, and 256 channels, and a memory capacity

of 10^6 counts per channel. The dead-time is 14 μ sec plus 0.5 μ sec per addressed channel number. When used with the RCL Model 21310 Basic Selective Storage, the analyzer operation is expanded because the number of inputs increases from one to four. All analog pulse input pulses are summed in the selective storage unit and processed by a single analog-to-digital converter (ADC) in the multichannel analyzer. Separate logic pulses, associated with the individual analog pulses, perform selection of memory sub-groups in which the digitized energy information is to be stored. To permit full use of the dynamic range of the pulse shape discrimination system (0 - 10V) the gain of the summing amplifier in the selective storage unit, having a range of only 0 - 5V, was decreased by a factor of 2. The summing amplifier and the ADC are DC-coupled.

The conversion gain of the ADC, nominally 5V full scale, was found to be typically 4.5V full scale. Therefore, a system output of 9V corresponds to the full scale channel on the multichannel analyzer. This level is sufficiently below the clipping level of 11V to prevent distortion of the uppermost portion of the recorded spectrum due to pile-up of the clipped pulses.

The timing sequence of the ADC and the Basic Selective Storage is shown in the lower part of Figure 22. The pulse analysis sequence in the multichannel analyzer is initiated by the base line level discriminator (BLD). The BLD exhibits considerable walk and causes nonlinearity problems with the particular pulse shape used (linear output, 409). This can be minimized by careful adjustment of the BLD and the lower level discriminator on the ADC. After careful adjustment of the ADC no greater deviations than 0.5 channels from a straight line through zero were found (0 - 127 channels). No

satisfactory analysis of pulses in channels 1 to 5 could be obtained. Therefore the data contained in channels 1 - 5 were not used.

3.6 Monitor System.

For performance checks and adjustment of parameters a "Twinkle Box" arrangement was used. This device displays on a cathode ray tube the energy signal versus some corresponding pulse shape information (Ref. 32, 33). In this monitor system the stretched energy pulse (X-input) is displayed versus the time processing channel information associated with it (Y-input) for the duration of the linear gate logic pulse (Z-input). A Tektronix type RM561 oscilloscope with type 75/3A75 plug-in units was used. The plug-in unit used for X-deflection was modified to obtain intensity modulation of the cathode ray tube (unblanking for the duration of the Z-pulse). The necessary modification is shown in Figure 24.

4. PERFORMANCE OF THE COMPLETE SPECTROMETER SYSTEM

All following performance data were obtained using a discrimination system as represented by the block-diagram, Figure 21, and using the multi-channel analyzer described in Section 3.5.

4.1 Dynamic Range Problems.

The dynamic range of the spectrometer system is restricted due to the limited performance of some of the modules. These limitations are as follows:

(a) The pulse height range of the Time-Pickoff-Unit is restricted to less than 30:1. If this range is exceeded, one or more spurious pulses appear at the negative logic output (duration 20 nsec) following the correct

timing pulse. When using the positive logic pulse (duration 400 nsec) for timing, this presents no problem: All spurious pulses occur within the pulse width of the first (correct) timing pulse and do not produce additional (erroneous) pulses.

(b) The pulse height range of the Zero-Crossing-Detector is restricted to less than 40:1 when using an integration time constant of 0.5 μ sec in the main amplifier. While this wide range for acceptable walk appears to present no limitation, the dispersion of the zero-crossing time increases with decreasing pulse height and imposes a practical limit of 25:1 at the highest system gain used (see Section 4.5).

(c) The multichannel analyzer can be used only in the range from channel 5 to channel 127. The resulting pulse height range is therefore 25:1.

To cover the range of interest for gamma and neutron energies (0.1 to 10 MeV and 0.5 to 15 MeV respectively), two levels of gain were selected; they are referred to in the following sections as "High Gain" and "Low Gain". The High Gain calibration is performed by adjusting the high voltage on the photomultiplier: Using sodium - 22 (Na-22) gamma rays, the high voltage is adjusted so that the extrapolated end-point of the measured continuous distribution falls in channel 92 ± 0.5 (1.067 MeV maximum electron energy). Using the arrangement of Figure 5, typically 2000 V are required. The Low Gain is lower by a factor of 7.50. The time constants used in the final system are the following:

(a) Photomultiplier current integration: $T = 2 \mu$ sec.

(b) Shaping amplifier integration: $T_i = 0.5 \mu$ sec.

(c) Double delayline shaping: $T_{d1} = T_{d2} = 0.8 \text{ } \mu\text{sec.}$

The energy thresholds, expressed in electron energies, are as follows:

High Gain: lower energy: 50 keV
 zero crossing: 40 keV
 Channel 5: 60 keV

Low Gain: lower energy: 50 keV
 zero crossing: 300 keV
 Channel 5: 450 keV.

Most of the results presented in the following sections were obtained using the above parameters.

4.2 Energy Response and Resolution for Gamma Rays.

The dominating interaction of gamma rays in stilbene is compton scattering. The resulting continuous energy distribution of the compton electrons extends from zero to a maximum compton electron energy, $E_{c \text{ max}}$, determined by the following:

$$E_{c \text{ max}} = E_{\gamma} \left[1 - \frac{m_0 c^2}{2E_{\gamma}} \right] \quad (10)$$

E_{γ} --- incident gamma ray energy

$m_0 c^2 = 0.511 \text{ MeV}$, rest energy of the electron.

The response of stilbene to electrons is linear with energy. The electron energy scale is therefore a convenient common pulse height reference scale.

The theoretical shape of the compton electron energy distribution (Ref. 35) is shown in Figure 25. The experimentally measured distribution,

broadened by scintillation statistics, is shown below the theoretical spectrum. The edge of the measured compton electron spectrum can be described with sufficient accuracy by the pulse heights P, C, H, and E. P (Peak) is the pulse height associated with the maximum of the measured distribution, H (Half point) the half maximum point on the compton edge, while E (End point) and C (Corner) are obtained as intersects of the tangent through the inflection point of the compton edge. This tangent coincides for all practical purposes with the best straight line drawn through the measured data points on the compton edge.

The set C, H, and E can be determined from experimental data consistently with much greater accuracy than the pulse height of the peak of distribution, P. The use of P is therefore not recommended. The true compton edge, $E_{c \text{ max}}$, is located between the energies corresponding to C and H (see Appendix 5).

The gamma energy response of the system was obtained by measuring the spectra of gamma sources of known energy. The source energies cover a range of 0.332 MeV (Chromium-51) to 1.837 MeV (Yttrium-88). The pulse height channels, corresponding to the points P, H, and E, are related to the maximum electron energy by the following expressions (units in channel numbers and MeV):

High Gain:

$$\begin{aligned} C_P &= 77.90 (E_{c \text{ max}} - 0.040) \\ C_H &= 82.20 (E_{c \text{ max}} - 0.015) \\ C_E &= 86.25 \cdot E_{c \text{ max}} \end{aligned} \tag{11}$$

Low Gain:

$$\begin{aligned}
 C_P &= 10.4 (E_{c \max} - 0.040) \\
 C_H &= 11.0 (E_{c \max} - 0.015) \\
 C_E &= 11.5 \cdot E_{c \max}
 \end{aligned}
 \tag{12}$$

It can be observed that these relations are straight lines intersecting the energy axis at 40 keV, 15 keV and zero respectively. The channel numbers corresponding to the maximum compton energy, $E_{c \max}$, are of a value between C_H and C_P (Figure 25) and will therefore be located on a straight line intersecting the energy axis at an energy between 15 and 40 keV, probably closer to the value of 15 keV. This is in good agreement with the value of 22 keV obtained by direct electron excitation of stilbene (Ref. 37).

The system resolution can be determined from relations between the pulse heights P, C, H, and E. Formally, several definitions of the resolution are possible:

For the case of a plastic scintillator similar in performance to stilbene, Jinuma and Burch (Ref. 38) observe that the shape on the high energy side of the peak is a good approximation to a Gaussian distribution. By associating the compton edge with the pulse height of the peak of the distribution, they define the resolution as follows:

$$R = 2 \frac{H - P}{P} \cdot 100$$

The resolution may also be defined by using the following relations:

$$\begin{aligned}
 R_1 &= \frac{E - C}{H} \cdot 100 = 2 \frac{E - H}{H} \cdot 100 \\
 R_2 &= \frac{E - P}{P} \cdot 100 \\
 R_3 &= \frac{E - P}{H} \cdot 100
 \end{aligned}
 \tag{13}$$

All of the above stated definitions may be used to compare on a relative basis the resolutions of different scintillators and systems. However, it is possible to select one definition based on physical properties of the scintillator. The theoretical resolution of a scintillation detector is energy dependent and is described by Equation 14:

$$R = \frac{\lambda}{\sqrt{E_{c \text{ max}}}} \quad [\%, \text{ MeV}] \quad (14)$$

For stilbene, λ equals 12.5 if it is assumed that for every 2 keV absorbed in the scintillator one photoelectron is produced by the photocathode of the photomultiplier (Ref. 34).

Using experimental gamma calibration data, resolutions were calculated as defined by Equation 13. The results, plotted on logarithmic scales are shown in Figure 26. The energy dependence defined by Equation 14 (a straight line with a slope of -0.5) was fitted to each set of data points. The values of λ corresponding to the best fit of R_1 , R_2 , and R_3 are 12.5, 17.5, and 14.0. The resolution measure R_1 results in a value of λ which agrees with the expected value of 12.5. Therefore the resolution defined as R_1 appears to be the most applicable for stilbene under these conditions. This is further substantiated in Appendix 5.

4.3 Energy Response and Resolution for Neutrons.

The neutrons interacting with stilbene produce recoil protons in the scintillator itself. The energy spectrum of the recoil protons extends from zero to a maximum energy equal to that of the incident neutrons.

The theoretical shape of the proton recoil spectrum (Ref. 35, 39) is shown in Figure 27, considering only scattering from hydrogen, and carbon to hydrogen. The shaded area represents the recoil protons produced by neutrons scattered from carbon and then to hydrogen. Below, the experimentally obtained pulse height distribution is shown on a linear proton energy scale. The pulse height values C, H, and E, are obtained in a manner similar to that for the case of the compton electron spectrum. H is identified with the neutron energy (see Appendix 5). The results obtained by calibration with monoenergetic neutrons are shown in Figures 28 and 29. The graphs also show the values of channel number corresponding to C and E (C is below E_n , E is above E_n , E_n is the incident neutron energy). The following analytic relations were obtained as fits to the experimental data:

$$\text{High Gain: } C_H = 13.5 \cdot E_n^{1.5} \quad (15)$$

$$\begin{aligned} \text{Low Gain: } C_H &= 1.80 \cdot E_n^{1.5} \\ E_n &< 8.7 \text{ MeV} \end{aligned} \quad (16)$$

$$\begin{aligned} C_H &= 5.23 \cdot E_n \\ E_n &\geq 8.7 \text{ MeV} \end{aligned} \quad (17)$$

These relations were obtained from preliminary calibration data and apply for one particular orientation of the scintillator only (Ref. 36). The relations are in good agreement with previously reported data for stilbene (Ref. 29).

Assuming the resolution of the spectrometer system is determined entirely by scintillation statistics, the resolution for neutrons is expected

to depend only on pulse height and to be of a form described by Equation 14, provided the nonlinear relation between proton and electron pulse height is considered. The resolution, consistent with the relative relation between proton and electron pulse height, and the value of $\lambda = 12.5$ as obtained for electrons, is then described by the following equations:

$$\left. \begin{aligned} R &= 30 \cdot E_n^{-0.75} \\ E_n &\leq 8.7 \text{ MeV} \end{aligned} \right\} \quad (18)$$

$$\left. \begin{aligned} R &= 18 \cdot E_n^{-0.5} \\ E_n &\geq 8.7 \text{ MeV} \end{aligned} \right\} \quad (19)$$

These relations, and the experimentally obtained values for the resolution defined as $R = \frac{E - C}{H} \cdot 100$ are shown in Figure 30. Corrections for neutron energy spread due to target thickness were not applied. A good fit for the experimental data is obtained for neutrons produced by a "thin" target ($350 \mu\text{g}/\text{cm}^2$, water spray for cooling). For comparison, the data obtained from a "thick" target ($2 \text{ mg}/\text{cm}^2$, water jacket) is also shown.

4.4 Relative Pulse Height Relations For Stilbene.

By using the results of the two previous sections, the relative relations of pulse heights for the various exiting particles can be found. The equivalent electron energies of maximum compton electrons due to gamma rays (E_γ - curve) and maximum recoil protons due to neutrons (E_n - curves) are plotted as a function of incident energy in Figure 31. Data for alphas and carbon recoils, obtained from M.McN. Wasson (Ref. 29) are also included.

It should be pointed out that these relations depend on the time constants used in the energy processing channel (T , T_i , T_{d1} , T_{d2}) and apply for a time constant selection as stated in Section 4.1 only.

The analytic expressions for the pulse height relations are summarized below (energies in MeV):

$$E_{c \text{ max}}: E_e = E_{c \text{ max}}, \text{ proportional to pulse height}$$

$$E_{\gamma} : E_e = E_{\gamma} \left[1 + \frac{0.511}{2E_{\gamma}} \right]^{-1}$$

$$E_n : E_e = 0.157 E_n^{1.5}$$

$$E_n \leq 8.7 \text{ MeV}$$

$$E_e = 0.455 E_n$$

$$E_n \geq 8.7 \text{ MeV}$$

$$E_{\alpha} : E_e = 0.043 E_{\alpha} + 0.006 E_{\alpha}^2$$

$$E_c : E_e = 0.016 E_c$$

(20)

4.5 TIMING PERFORMANCE AND NEUTRON-GAMMA DISCRIMINATION.

The timing performance of the complete system was investigated using a fast risetime mercury pulse generator. The output pulses were shaped by constant impedance networks of 5 and 100 nsec risetimes and applied to the input of the preamplifier. The maximum input pulse height was adjusted to obtain the energy signal close to full scale on the multichannel analyzer which was 511 channels for this particular test. While an energy resolution of better than 0.2 percent of full scale was obtained over the whole range, amplitude dependent dispersion and shift of the associated time spectra were observed. The dependence of the maxima and half-maxima of the time spectra on pulse height is shown both for High Gain and Low Gain in Figure 32. The dispersion

is nearly independent of pulse shape and decreases with increasing pulse height (energy). For the slow pulse at High Gain a pronounced shift of the time spectrum was found. This shift was caused by the time pickoff unit (see also Figure 9). In addition to the shift, the lower energy threshold was found to be dependent on risetime as can be seen from Figure 32 (see High Gain, fast and slow pulse).

The performance determined by this test does not include the influences due to the statistical nature of the signals in actual operation. These influences are included in the following tests which were obtained with radiation incident on the stilbene crystal (gammas, neutrons and gammas):

The first test was performed with monoenergetic neutrons of 4.1 MeV energy and associated gamma rays. An additional Co60 calibration source placed on the scintillation crystal produced comparable electron and proton counting rates. A lower energy threshold of 50 keV equivalent electron energy was established by the time pickoff unit. Results for integration time constants of the shaping amplifier of 0.2, 0.5, and 1.0 μ sec are shown in Figure 33. Later investigations proved the integration time constant of 0.5 μ sec allowed the best discrimination between protons and electrons for low pulse heights.

Graphic integration of the time spectrum for 0.5 μ sec integration time gives following results:

(a) The areas under the gamma and neutron peaks are 304 ± 4 and 597 ± 6 . These areas are proportional to the total number of electrons and protons produced in the crystal.

(b) The two peaks are not completely separated; therefore some electrons will be counted as protons and vice-versa. The following estimates were obtained:

electrons identified as protons: 4 ± 2

protons identified as electrons: 6 ± 3 .

These numbers indicate a discrimination ratio of only 100:1. However, the time spectrum needs careful interpretation because it is the distribution of all pulses admitted for analysis by the lower energy threshold (time pickoff discriminator). For good timing performance, this threshold needs to be set lower than required for energy analysis. The recorded time spectrum will therefore always contain excess pulses corresponding to energy pulses not recorded on the energy spectrum (channels 5 and below). This is not immediately evident from the time spectrum and a convenient shape parameter of that spectrum, like the peak-to-valley ratio, does not represent a suitable discrimination measure for the recorded energies. The actual energy (pulse height) dependent discrimination measure, most conveniently obtained with a two-parameter multichannel analyzer, is always higher than that obtained from the time spectrum alone. In fact, discrimination ratios in excess of 1000:1 are generally obtained.

The time-spectrum was also obtained from a Plutonium-Beryllium neutron source (Pu-Be) and the results are shown in Figure 34. The experimental conditions were as follows:

- (a) Energy calibration: Low Gain
- (b) Shaping: standard HENRE
- (c) Lower energy threshold: ~ 50 keV
- (d) Zero crossing threshold: ~ 300 keV
- (e) Preamplifier cable: 150 feet.

Peaks corresponding to electrons (gammas) and protons (neutrons) exhibit

a full width at half maximum of 7.8 nsec and 24 nsec. The separation between the peaks is 42 nsec. A third peak associated with energy pulses of insufficient amplitude to trigger the zero crossing detector is observed at full scale of the TPHC. This pulse serves as a convenient reference for time calibration. The relative intensities in terms of output pulses of the time processing channel are as follows:

identified gamma (channels 1-62): 29663
identified neutrons (channels 62-82): 32090
not identified low energy (channels 82-85): 58647
spurious (channels 85-127): 45
total (channels 1-127): 120445

The wings of the measured distributions are straight lines on a semilog-graph (Figure 34) and the individual shapes of the electron and proton distributions can be extrapolated with good justification. For a discrimination level established at the first minimum (channel 62) the following numbers are obtained:

gammas identified as neutrons: 24
neutrons identified as gammas: 24.

Thus discrimination ratios in excess of 1000:1 are obtained from the total time spectrum, not considering any of the complications outlined before. The discrimination ratio can be further improved by rejecting both electrons and protons at the minimum between peaks. The results of rejecting 5 channels of information are as follows:

rejected gammas and neutrons (channels 59-64): 598
gammas identified as neutrons: less than 1
neutrons identified as gammas: less than 1.

A discrimination ratio of greater than 3×10^4 is obtained under these conditions at the expense of less than 2 percent counting losses.

The time spectra obtained with monoenergetic neutrons and associated gammas over the neutron energy range from 0.78 MeV to 16.7 MeV are summarized in Figure 35. The maxima and half-maxima of the measured distributions are plotted versus incident neutron energy. At higher neutron energies alpha reactions in the scintillator can be identified and discriminated against if so desired.

4.6 Rate Dependence.

The rate dependence of the energy channel imposes practically no limitations provided the unipolar energy pulses from the linear gate (ORTEC 409, See 3.2) are DC coupled to the multichannel analyzer. This was demonstrated by analyzing only gammas from a Co 60 source and admitting all pulses from the time processing channel as gate pulses for the energy channel. The extrapolated end points of the compton edges (C_E) and the peaks (C_P) of the obtained spectra were found to vary less than 2 percent for count rates up to 100,000 counts per second. Immediately following prolonged operation with high count rate a slow gain increase of as much as 6 percent was usually observed; this increase was attributable to the photomultiplier. However, the recorded spectra did show count rate dependent shape differences for pulse heights below 0.2 MeV equivalent electron energy.

Count rate limitations imposed by the time processing channel are more severe as outlined in Section 3.3.4. The rate-dependent timing performance of the complete system was investigated for the two selected

ranges by analysis of the time spectrum. The output rate of the time processing channel was determined from the data obtained by a multichannel analyzer operated for a fixed "Live-Time". Pile-up effects of the analyzer and the four-input selective storage unit are included in the following results. The experimental conditions for the two cases are as follows:

(a) High Gain: Source: Co60

Lower energy threshold: 50 keV

zero crossing threshold: 40 keV

Delay: 100 ns

Time scale: 3 ns/channel

(b) Low Gain: Source: Pu-Be

Lower energy threshold: 50 keV

Zero crossing threshold: 300 keV

Delay: 1100 ns

Time scale: 3 ns/channel.

The results obtained for case (a) are shown in Figure 36. The deadtime for this case is equal to the set delay (1100 nsec). By introducing additional deadtime in the delay generator the performance can be improved. These results are shown in Figure 37. A deadtime of 6 μ sec total was used. For case (b) the results are shown in Figure 38.

In both cases a degraded resolution and a shift of + 3 nsec can be observed for the full scale pulse of the TPHC. The resolution and position of this peak is in no way affected by the delay generator (BRL 400D) or the zero crossing detector (ORTEC 407), therefore these effects are probably caused by the TPHC and associated shaping amplifier, the four-input selector and

possibly the ADC of the multichannel analyzer. For higher rates it can also be observed that the intensity of the full scale peak increases by a larger amount than expected from the relative source intensity; this behavior indicates that the zero-crossing detector threshold increases with higher count rate.

For simultaneous accumulation of both gamma and neutron energy spectra (normal operation), the selective storage unit (RCL 21310) used for memory sub-group switching and also the time-processing channel imposes strict limitations. A sub-group selection error of 1 part in 10^3 is observed for operation at rates exceeding 5000 pulses per second. For rates below 1000 pulses per second the sub-group selection error was found to be less than 1 part in 10^4 . The gated time spectrum of Pu-Be, accumulated simultaneously in two memory sub-groups of the multichannel analyzer, is shown superimposed in Figure 39. The complete (ungated) time spectrum is also shown. This test was performed at the maximum rate for good discrimination (5300 counts per second output rate of the time processing channel, ungated). The experimental conditions for this test were identical to the test described in Section 4.5 (Figure 34) with two exceptions: the count rate was higher and a longer signal cable was used between the preamplifier and the system input.

Analogous to Section 4.5 the following results were obtained from the complete time spectrum:

identified gamma (channels 1-62)	:	147,579
identified neutron (channels 62-83)	:	151,502
not identified low energy (channels 84-86)	:	233,509
spurious (channels 87-127)	:	552
Total (channels 1-127)	:	533,142

The time spectrum accumulated simultaneously in different memory sub-groups of the same analyzer (the gated time spectrum) gives for the same live-time accumulation of 100 sec the following results:

(a) Gamma Sub-Group:

positively identified gamma (channels 0-62):	146,885
probable neutron and spurious (channels 63-127):	825

(b) Neutron Sub-Group:

positively identified neutrons (channels 62-83):	147,233
probable gammas (channels 1-61):	243
probable low energy and spurious (channels 84-127):	644

This is the discrimination achievable at the limiting rate of 5.3×10^3 pulses per second at the ungated time processing channel output. Better discrimination can be achieved at lower rates. It should be again pointed out that any discrimination figure determined from the time spectrum alone is lower than that of the actual recorded neutron and gamma energy spectra.

4.7 Signal Cable Limitations

The rise time of a signal being transmitted through a properly terminated cable increases with the square of the cable length, and the entire shape of the signal is degraded in a complex fashion (Ref. 21). The discrimination properties of the complete spectrometer system depend only on pulse shapes. Therefore, the properties will be subjected to variations caused by different lengths of cable between preamplifier and system input.

However, the influence of the cable length on pulse shape discrimination is surprisingly mild. This is demonstrated by a discussion of results already presented in the previous section. The results shown in Figure 39 were

obtained with a cable length of 1000 feet, all others including those shown in Figure 34, with 150 feet. The change in delay of the start pulse (made in BRL 400D) necessary to establish agreement of the location of the gamma peaks in the time spectrum for the two cases is 30 nsec. This indicates that the rise time of the preamplifier output pulse has been changed by about the same amount of time in passing through the additional length of signal cable. Two effects on the time spectrum caused by this rise time degradation can be observed by comparing Figure 39 with Figure 34. These effects are:

- (a) The separation between the electron and proton time distribution decreases slightly.
- (b) The resolution for both the electron and proton distributions improves to 5 nsec and 18 nsec from the previous values of 7.8 nsec and 24 nsec.

The first effect can be attributed to a decrease of rise time differences between proton and electron pulses. The second effect is caused by the rise time dependent trigger threshold of the time pickoff unit (low energy threshold). The energy threshold for the same discriminator setting is higher than in the previous test and is also pulse shape dependent. An increase of the relative neutron and gamma count rates at the expense of the full scale peak of the time spectrum is therefore expected. The gamma count rate (fast pulses) is expected to gain a greater share of the increase than the neutron count rate (slow pulses). This is demonstrated by comparing the relative counts in the table on the following page. These data were provided by the tests which produced the information shown in Figures 34 and 39.

	Count Rate	
	150 foot cable	1000 foot cable
Gamma	297	1476
Neutron	321	1515
Full Scale (TPHC)	586	2335
Neutron/gamma	1.08	1.02
Full Scale/gamma	1.97	1.58
Full Scale/neutron	1.82	1.54

The dependence of threshold behavior upon pulse shape is further substantiated in the next section. Results obtained from similar tests show that a cable length of up to 500 meters between preamplifier and system-input can be tolerated, causing practically no degradation of the discrimination performance between neutrons and gammas.

4.8 Lower Energy Discrimination Limit

All results in this section have been obtained from photographs of the monitor display (see Section 3.6) using Pu-Be as a source of radiation. A linear electron energy scale for the pulse heights is assumed. Typical results for standard High Gain conditions are shown in Figure 40, top.

The pertinent parameters for this case are as follows:

- a. Photomultiplier - Preamplifier: Dynode 12
A = +2.00
- b. High Voltage: +2020V, Na-22 extrapolated compton edge in channel 92
- c. Cable: 150 feet
- d. Discriminator: 3.00 (Dial)
- e. Scale (on Monitor): X:180 keV/cm
Y: 50 ns/cm
- f. Zero crossing threshold: 40 keV.

The following information can be obtained from the photograph:

(a) Low energy threshold for above discriminator setting:

electrons: ~ 54 keV

protons: ~ 72 keV.

(b) Separation between protons and electrons is excellent down to 100 keV.

(c) At the right, two bright spots can be observed, corresponding to the clipped energy pulses for this gain setting. These pulses would, of course, be included in the corresponding time spectrum. The time spectrum would therefore give an incorrect picture of the discrimination properties.

An attempt was made to determine the minimum equivalent electron energy for which discrimination between protons and electrons is possible. For this test the anode output of the photomultiplier was used with the preamplifier connected for a gain of -1.00 (Figure 4).

Except for higher gain and lower thresholds the experimental conditions were the same as previously. The resulting display is shown in Figure 40, bottom. The energy scale is 33 keV/cm, the time scale 50 nsec/cm. For the shaping time constants used (double delay line 0.8 μ sec, $T_1 = 0.5$ μ sec) the lowest electron energy for "good" proton-electron discrimination can be estimated to be 33 keV. No separation is obtained below 22 keV.

The influence of the shaping time constants on the minimum discriminated electron energy was investigated for a fixed charge conversion time constant of 2 μ sec. Double delayline shaping consistently discriminated lower electron energies than R-C shaping. The results for double delay

line shaping with 0.8 μ sec delay lines and a variable integration time constant of the shaping amplifier are shown in Figure 41. Two curves are shown: $E_{\min}$, the minimum estimated electron energy for good separation, and $E_{\max}$, the maximum estimated electron energy for no separation. Both curves show a broad minimum for an integration time constant of 0.5 μ sec, close to the time constant used for double delay line shaping. Therefore, for lower energy thresholds above 33 keV, as commonly used on both Low Gain and High Gain, nearly perfect discrimination can be expected.

While the experimentally obtained figure of about 22 keV separable electron energy compares favorably with the best recent reported data (32 keV, Ref. 29), it is interesting to consider the minimum possible energy for proton-electron separation. M.McN. Wasson (Ref. 29) states that 18 photoelectrons are required to give the minimum separable pulse height for stilbene. This number is based on the ratio of the fast and slow components of the scintillation decay and is therefore applicable to the discrimination technique used here (See Section 2.0). By assuming a photoelectron yield of 1.2 electrons per keV energy loss in stilbene, M.McN. Wasson obtains 15 keV for the minimum separable electron energy.

For low electron energies, the nonproportional response of stilbene needs to be considered (see Section 4.2 and Ref. 36) so about 22 keV should be added to the figure above; this gives approximately 37 keV minimum separable electron energy (15 keV on a pulse height scale). If on the other hand a photoelectron yield of 0.5 photoelectrons per keV energy loss is assumed (Ref. 34, see also Section 4.2) the minimum separable electron energy becomes 36 keV, this corresponds to about 14 keV on the pulse height scale.

In view of these considerations, the experimentally determined minimum separable electron energy (22 keV, pulse height scale) is found to be significantly higher than the theoretical limit of 14 - 15 keV. Further refinements of the system may improve this minimum discriminated energy.

Figure 41 also shows the time differences between the peaks of the proton and electron distributions at one equivalent electron energy (150 keV). These time differences are found to be larger than those obtained at higher energies (see Figure 35). By using different energy to voltage conversion factors (anode output, dynode output, different high voltage) it can be shown that these time differences are dependent only on energy and not on pulse height delivered to the discrimination system. This behavior can therefore be attributed to the scintillator itself, in this case stilbene.

Generally it was found that the electron distribution maximum, as obtained from gamma rays from Pu-Be varies less than 7 nsec over the entire energy range; the zero crossing time increases slightly with energy, but again is independent of system pulse height. The proton distribution (neutrons from Pu-Be) exhibits the reverse effect; with the energy dependence more pronounced. These effects also explain the different exponential slopes which can be observed, especially on the proton distributions of the total time spectra as presented in Sections 4.5 and 4.6.

5. COUNTING OPTIONS OF THE SPECTROMETER SYSTEM

In addition to simultaneous accumulation of two or more particle related energy spectra, the system offers access to various logic pulses. For neutron-gamma discrimination, single channel analyzer adjustments corresponding to

Figure 39 are assumed. The various pulses and their relation to the measured spectra are listed below:

- (a) All pulses above lower energy threshold:
Access: BRL 400 SD, all outputs
Double pulse resolution: $< 1 \mu\text{sec}$
Maximum rate: 10^5 pps.
- (b) All pulses admitted for energy analysis:
Access: ORTEC 409, gate output pulse
Double pulse resolution: greater then set delay on BRL 400D
Pile-Up time: determined by time-to-pulse height converter and associated shaping amplifier.
Maximum rate: 5×10^3 pps, with limited accuracy 25×10^3 pps.
- (c) All pulses admitted for energy analysis recognized as gammas:
Access: BRL 400 RL, A-input
Limitations: as in b.
- (d) All pulses admitted for energy analysis recognized as neutrons:
Access: BRL 400 RL, B-input
Limitations: as in b.
- (e) All pulses above threshold less recognized gammas admitted for energy analysis:
Access: Upper level discriminator output of the single channel analyzer selecting gammas.
Limitations: as in b.
- (f) All pulses above threshold less recognized gammas and neutrons admitted for energy analysis:
Access: Upper level discriminator output of the single channel analyzer selecting neutrons.
Limitations: as in b.
- (g) Total output pulses of the time processing channel:
Access: Lower level discriminator output of the single channel analyzer selecting gammas, provided the lower level is set to include all gamma pulses.
Limitations: as in b.

The relative count rates of these pulses provide valuable information in addition to the recorded energy spectra and time spectra. These pulses can be used for monitoring purposes and for detailed analysis of the operation of the entire spectrometer system.

6. SUMMARY

The development described in this report has provided an operational spectrometer system which simultaneously analyzes and records neutron and gamma ray spectra. The energy region of interest is covered in two ranges (High Gain and Low Gain):

High Gain:

Channel Number	Electron Energy	Gamma Energy	Neutron Energy
5	60 keV	150 keV	500 KeV
127	1.4 MeV	1.6 MeV	4.2 MeV

Low Gain:

Channel Number	Electron Energy	Gamma Energy	Neutron Energy
5	0.45 MeV	0.5 MeV	2 MeV
127	11 McV	11 McV	20 MeV

On High Gain, excellent discrimination between neutrons and gamma rays is possible for pulse heights exceeding 100 keV electron energy. This corresponds to neutron and gamma ray energies of 700 keV and 220 keV respectively. On both High Gain and Low Gain, the discrimination ratio between the recorded neutron and gamma ray energies (channels 5 and above) exceeds 1000:1. No frequent or critical adjustments are required to meet or to exceed this figure, even under field conditions. With the present system the lower discrimination limit is 22 keV electron energy (90 keV gamma energy, 270 keV neutron energy).

The spectrometer system is capable of performing the task for which it has been developed, namely the field measurements of neutron and gamma ray spectra transmitted through radiological shields (Ref. 36). In addition, it also made measurements of the same kind under laboratory controlled conditions (Ref. 40). The limitations of the system were clearly recognized, the most obvious being the somewhat limited countrate capability (5000 counts per second for precision analysis).

Many possible modifications that would improve the performance of the system were recognized during the development. It appears that simplifications of the instrumentation system are possible without any sacrifice of performance. Any such changes will limit the flexibility and adaptability of the pulse-shape discrimination system and could be justified only once a definite choice of the scintillation material is made. As pointed out previously the scintillator, stilbene, was chosen for its superior response to gamma rays. The neutron response is complicated to some degree by the anisotropic directional dependence of the stilbene crystal. With the current increasing reliance on this spectrometer for neutron measurements it is possible that other scintillators will be selected in future applications. In that case, an instrumentation package tailored to the particular needs of a specific scintillator would be developed and better overall performance and operation at a much faster rate would be anticipated.

KONRAD FRANK

FIG.1 SIMPLIFIED BLOCK DIAGRAM OF SYSTEM

FIG. 2 SIGNALS FOR EXPONENTIAL SCINTILLATION DECAY

FIG. 3: VOLTAGE DIVIDER CIRCUIT FOR 56AVP

- NOTE 1: ALL RESISTORS $\leq 22K$ ARE $1W \pm 5\%$
 2: ALL RESISTORS $> 22K$ ARE $2W \pm 5\%$
 3: ALL CAPACITORS ARE $20 \text{ nF}/500V \pm 10\%$ UNLESS OTHERWISE NOTED
 4: $Z_{12}, Z_{13}, Z_{14}, Z_A$ ARE $33\Omega, 0.5W \pm 10\%$ WHEN NOT USED FOR SIGNAL TAP-OFF
 5: MINIMUM OPERATING VOLTAGE WITH 56AVP IS 1860V (80V MINIMUM BETWEEN DYNODES)
 6: GAIN FACTOR: $\frac{\Delta G}{G} \approx 10^{-2} \cdot \Delta V [V]$, ANODE OUTPUT
 7: NOMINAL ADJUSTMENTS:
 G1: $E_{G1} \approx E_C + 5V$
 G2: $E_{G2} \approx E_{D1}$
 8: TOTAL VOLTAGE DIVIDER RESISTANCE: $\sim 510 K\Omega$
 9: NO CONNECTION TO PIN # 9
 10: $\delta_n \approx 3 \cdot 10^{-2} \cdot (E_{Dn} - E_{Dn-1})$; $\Delta E_{Dn, n-1} \leq 300V$
 11: MECHANICAL: PRINTED CIRCUIT 56AVP MOUNTED IN BRL568

FIG. 4 BRL - 568, PM-PREAMPLIFIER AND SIGNAL CONDITIONER,
CONNECTED FOR ANODE OUTPUT.

NOTE: PREAMPLIFIER SHOWN FOR $A = -1$;
FOR GAIN $A = -0.1$: $R_1 = 100\text{ K}$, $R_2 = 10\text{ K}$,
 C_T PARALLEL TO R_2 ;

FIG. 5 BRL - 568, PM-PREAMPLIFIER AND SIGNAL CONDITIONER,
CONNECTED FOR DYNODE OUTPUT.

NOTE: PREAMPLIFIER SHOWN FOR A = +2 ;
R₄ = 10 k Ω FOR 2 μ S DECAY TIME CONSTANT
R₄ = 100 k Ω FOR 20 μ S DECAY TIME CONSTANT

FIG. 6 LOW-LEVEL AMPLIFIER PRINTED CIRCUIT CARD Ω 0IXL

1. C_T : 2—8pF TRIMMER, NPO.

2. D1, D2: FAST RECOVERY SILICON DIODES.

3. Q1, Q2: 2N2484, 2N3227, ME213, ME4003; Q3=2N2219

4. RESISTORS MARKED* 1/8 W METAL FILM, ALL OTHERS 1/4 W CARBON EXCEPT WHEN NOTED OTHERWISE.

5. CAPACITOR VALUES IN μ F UNLESS OTHERWISE NOTED.

FIG. 7 BRL 568, Co60 PEAK PULSE HEIGHT VS. HIGH VOLTAGE

FIG. 8 FIVE-INPUT MIXING AMPLIFIER - BRL 400 MA
STANDARD MODULE, SINGLE WIDTH

+ IN : NONINVERTING INPUTS, 4 IDENTICAL CIRCUITS
GAIN ADJ : 75 - 100 % OF SET GAIN; APPROX 1 % / TURN

- IN : INVERTING INPUT

RESISTORS MARKED WITH * : 1% METAL FILM

GAIN	0	1/4	$\sqrt{2}/4$	1/2	$\sqrt{2}/2$	1	$\sqrt{2}$	2	$2\sqrt{2}$	4	$4\sqrt{2}$
R_g * (Ω)	—	8250	5900	4020	2870	2000	1400	953	649	432	274

FIG. 9 TIME-SLEWING OF START PULSE

FIG. 10 VARIABLE DELAY MODULE BRL 400D
400 - 1400 nsec

FIG. 11 TUNNEL DIODE FAN-IN CIRCUIT

NOTES:

1. RESISTORS: 0.5 W CARBON
2. CAPACITORS: μF UNLESS OTHERWISE NOTED
3. $\bigcirc$ COMPONENT RECEPTACLE ON BOARD
4. $R_T = 12.7\text{ K} \pm 1\% \text{ MF}$
 $C_T = 200\text{ pF} \pm 5\% \text{ DM}$ } FOR 400-1400 ns RANGE
5. D1-D5: FAST RECOVERY SI-DIODES
 IN907/908, IN4151.

6. D6: TD-2A (2.2mA) OR TD-3A (4.7 mA)
7. Q1: 2N706M, 2N708
 Q2: 2N709, 2N706, 2N708
 Q3: 2N2904/2905
 Q4: 2N2219/18
 Q5: 2N964/700/711B/2048/2904/2905

FIG. 12 PRINTED CIRCUIT BOARD $\Delta 02$ DELAY GENERATOR
 22 - PIN CIRCUIT BOARD, KEY ON H7

FIG. 13 BRL 400D, DELAY CALIBRATION

FIG. 14 BRL 400D TIMING ERROR VS. RETRIGGER TIME

FIG. 15 CROSSOVER WALK

STANDARD MODULE, SINGLE WIDTH

$$A = 0.225 \text{ V/mA} \quad (Z = 500 \Omega)$$

FIG. 17-PRINTED CIRCUIT CARD A123

ALL RESISTORS: 0.25 W UNLESS OTHERWISE NOTED

FIG. 18 ROUTING LOGIC - BRL 400RL
STANDARD MODULE, SINGLE WIDTH

TRANSISTORS: ALL 2N706

RESISTORS: ALL 0.25 W CARBON UNLESS OTHERWISE NOTED

FIG. 19 Λ 01, OR-GATE, 1EA. ON Λ 122 CARD

FIG. 20 $\Lambda 02$, AND-GATE, 2 EA. ON $\Lambda 122$ -CARD

NOTES:

1. ORTEC-221 IS EQUIVALENT TO 410/0.8 + 407.
2. ORTEC-413: MODIFIED STROBE AND RESET, USE ON EXT. ONLY
3. ORTEC-405M: USE MODIFIED STOP-INPUT ONLY.
4. x, --- CONNECTIONS NECESSARY TO DISPLAY PSD SPECTRUM, (GATED BY 413'S)
5. 6PL6 IS A INTERFACE AND LINE DRIVER FOR 4 EACH 568 (STILBENE) AND 2 EACH RCL 20203 (NAT) PREAMPLIFIERS.
6. BRL-400SD: USE MODULES WITH M51Ω ONLY.
7. RCL 21310: SELECTIVE STORAGE UNIT.
8. CABLE TERMINATION, Z_0 : TEKTRONIX 011-056, 93Ω

				ENGINEER	SCALE
				J. DANTE	—
				DRAFTSMAN	DATE
				J.V. REEVES	7 MAY '65
				MATERIAL	
3		22 JUNE '65	K.F.	TOLERANCES	
2	1	12 MAY '65	K.F.	UNLESS OTHERWISE SPECIFIED	
1	1	27 APR. '65	K.F.	FRACTIONS ANGLES DECIMALS	
NO. REVISIONS DATE APP'D.				APPROVED BY	
				K. FRANK	

PROJECT - HENRE
BLOCK DIAGRAM
FOR
STILBENE DETECTOR
DISCRIMINATION SYSTEM

ORDNANCE CORPS
DEPT OF THE ARMY
BALLISTIC RESEARCH LABORATORIES
BRL - TBL - (NPB)

B-1954

SHEET | OF |

FIG. 21

ENGINEER K. FRANK		SCALE —
DESIGNED BY J. V. REEVES	DATE JUNE 22, 1965	
PROJECT - HENRE PULSE-TIME RELATION- SHIPS FOR PULSE-SHAPE DISCRIMINATION SYSTEMS SOLID STATE SPECTRO- METERS AND STILBENE DETECTORS		
ORDNANCE CORPS DEPT OF THE ARMY BALLISTIC RESEARCH LABORATORIES BRL - TBL - (NPB)		
C-1988		

FIG. 22

FIG. 23. ASSEMBLED SYSTEM (2)

NOTE: 1., INPUT VOLTAGE (PULSE) : ± 0.5 V MIN (UNBLANKING AND BLANKING)

2., USE MODIFIED MODULE FOR X-DEFLECTION

FIGURE 24 Z-INPUT FOR TYPE 75/3A75 PLUG-IN UNIT

FIG. 25 TYPICAL COMPTON ELECTRON SPECTRUM

FIG. 26 GAMMA RESOLUTION

FIG. 27 TYPICAL PROTON RECOIL SPECTRUM (STILBENE)

FIG. 28 PULSE HEIGHT vs. ENERGY (HIGH GAIN)

FIG. 29. PULSE HEIGHT VERSUS ENERGY (LOW GAIN)

FIG. 30 NEUTRON RESOLUTION

FIG. 31 PULSE HEIGHT RELATIONS FOR STILBENE

FIG. 32 TIME SPECTRA FOR 5 AND 100ns PULSES

FIG. 33 TIME SPECTRUM 4.1 MEV. NEUTRONS AND ASSOC. GAMMAS
WITH ADDITIONAL Co60 SOURCE

FIG. 34 Pu-Be TIME SPECTRUM (LOW GAIN) 99

FIG. 35 - TIME SPECTRA (NEUTRON AND ASSOCIATED GAMMAS)

FIGURE 37 Co 60 TIME SPECTRUM (HIGH GAIN 6 μ sec DEAD TIME)

FIGURE 38 Pu-Be TIME SPECTRUM (LOW GAIN), PILE UP EFFECTS

Pu - Be , "HIGH GAIN"
VERTICAL : 50 ns / div
HORIZONTAL : 180 kev / div

Pu - Be : VERTICAL : 50 ns / div
HORIZONTAL : 33 kev / div

FIGURE 40 PROTON-ELECTRON DISCRIMINATION (STILBENE , Pu-Be)

FIGURE 41 PROTON-ELECTRON DISCRIMINATION VS INTEGRATING TIME CONSTANT (STILBENE, Pu-Be)

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APPENDIX 1

PULSE SHAPES OBTAINED FROM SCINTILLATION COUNTERS

A parallel combination of a resistance R and a capacitance C is assumed for the load impedance of a photomultiplier. The following output voltage is then obtained:

$$e(s) = i(s) \cdot Z(s)$$

$$Z(s) = \frac{1}{C} \cdot \frac{T}{1 + sT} = \frac{1}{sC} \cdot \frac{sT}{1 + sT} \quad \quad \quad \} \quad (A1-1)$$

$$T = R.C$$

- $s = j\omega$ - complex frequency variable
- $Z(s)$ - load impedance, transfer impedance
- T - time constant
- $i(s)$ - transform of the output - current, $i(t)$, of the
 photomultiplier
- $e(s)$ - transform of the output-voltage.

The operation performed by the transfer impedance, $Z(s)$, is equivalent to an ideal integration of the photomultiplier current (term $1/sC$) and a subsequent RC-differentiation of the resulting voltage pulse (term $sT/(1+sT)$). Assuming an exponentially decaying current pulse, well-known relations for pulse-shapes of a scintillation counter are obtained (Ref. 1). These relations are summarized below and extended to cover special cases applicable to particular scintillators.

1. Exponential Scintillation Pulse

The fluorescence radiation of the scintillator is assumed to decay exponentially with a single time-constant τ . The output current of the photomultiplier shows then the same shape:

$$t < 0 : i(t) = 0$$

$$t \geq 0 : i(t) = I_{\max} \cdot \exp(-t/\tau) = \frac{Q}{\tau} \exp(t/\tau)$$

$$Q = \int_0^{\infty} i(t) \cdot dt = I_{\max} \cdot \tau$$

$I_{\max}$: peak current

Q : total charge contained in the current pulse.

Using Laplace-transforms, we obtain for this case the following relations:

$$i(s) = \frac{Q}{\tau} \cdot \frac{1}{s + 1/\tau} = Q \cdot \frac{1}{1 + s\tau}$$

$$e(s) = \frac{Q}{C} \cdot f(s) = \frac{Q \cdot R}{T} \cdot F(s) \quad \} \quad (A1-2)$$

$$F(s) = \frac{1}{1 + s\tau} \cdot \frac{T}{1 + sT}$$

The time-dependence of the voltage-pulse is obtained by the inverse Laplace-transform:

$$e(t) = \frac{Q}{C} \cdot f(t) = \frac{QR}{T} \cdot f(t)$$

$$f(t) = L^{-1} [F(s)] \quad \} \quad (A1-3)$$

The factor associated with the total charge, Q , consists of a constant ($1/C$, charge conversion gain, - factor) and a time-function, $f(t)$, which can assume a maximum value of one. All further discussions can be limited to the behavior of $f(t)$:

$$t < 0 : f(t) = 0$$

$$t \geq 0 : f(t) = \frac{1}{1 - \tau/T} [\exp(-t/T) - \exp(-t/\tau)].$$

Introducing the ratio between T and τ as an independent, dimensionless parameter, we obtain:

$$x = T/\tau, \quad t \geq 0:$$

$$f(t) = \frac{x}{x-1} [\exp(-t/T) - \exp(-t/\tau)]. \quad (A1-4)$$

The maximum of $f(t)$ can be found by differentiation:

$$\frac{d}{dt} f(t) = 0 : t = t_M$$

$$f(t_M) = f_M$$

$$t_M/\tau = \frac{x}{x-1} \cdot \ln x$$

$$f_M = (x)^{\frac{1}{1-x}} \quad (A1-4a)$$

In the following, special cases are considered:

1.1 Nearly Ideal Integration, $x \gg 1$, $T \gg \tau$

The previous equations reduce to the following form:

$$f(t) = \exp(-t/T) - \exp(-t/\tau)$$

$$t_M = \tau \cdot \ln x = \tau \cdot \ln \frac{T}{\tau} \quad \} \quad (A1-5)$$

$$f_M = 1 - \frac{1}{x} \doteq 1$$

For different time-regions, further approximations are useful:

$$\begin{aligned} 0 \leq t \ll T : f(t) &= 1 - \exp(-t/\tau) \\ \tau \ll t \leq \infty : f(t) &= \exp(-t/T) \end{aligned} \quad \} \quad (A1-5a)$$

1.2 Optimum Signal-To-Noise Ratio, $x = 1$, $T = \tau$

The time-function for this case is obtained from Equations A1-2 ($\tau = T$):

$$\begin{aligned} f(t) &= \frac{t}{\tau} \cdot \exp(-t/\tau) \\ t_M &= \tau \\ f_M &= \frac{1}{e} \doteq 0.368 \end{aligned} \quad \} \quad (A1-6)$$

1.3 No Integration, $x \ll 1$, $T \ll \tau$

The following relations are obtained from Equations A1-4:

$$\begin{aligned} f(t) &= x [\exp(-t/\tau) - \exp(-t/T)] \\ t_M &= \tau x \ln x = T \cdot \ln \frac{\tau}{T} \\ f_M &= (x)^{1+x} \doteq x \end{aligned} \quad \} \quad (A1-7)$$

Further useful approximations are the following:

$$\begin{aligned} 0 \leq t < \tau : f(t) &= x[1 - \exp(-t/T)] \\ T < \tau < \infty : f(t) &= x \cdot \exp(-t/\tau) \end{aligned} \quad (A1-7a)$$

For $T \rightarrow 0$ the trivial result, $e(t) = R \cdot i(t)$, is obtained.

2. RECTANGULAR SCINTILLATION PULSE

The current-pulse is simulated by a rectangular pulse of the same peak current and the same total charge:

$$\begin{aligned} t < 0 : i(t) &= 0 \\ 0 \leq t < \tau : i(t) &= I_{\max} \\ \tau \leq t < \infty : i(t) &= 0. \end{aligned}$$

This approximation is useful for scintillators exhibiting a very fast decay. For a large integration time constant T , the following pulse shape is found:

$$\begin{aligned} x \gg 1, T \gg \tau : \\ 0 \leq t \leq \tau : f(t) &= \frac{t}{\tau} \\ \tau \leq t < \infty : f(t) &= \exp(-t/T) \\ t_M = \tau, f_M &= 1 \end{aligned} \quad (A1-8)$$

3. MULTI-COMPONENT SCINTILLATOR PULSE

Two or more exponentially decaying components are used to approximate the fluorescence radiation of the scintillator, each component is of a form as used in Section 1:

$$\begin{aligned} t < 0 : i(t) &= 0 \\ t \geq 0 : i(t) &= \sum_j I_{mj} \exp(-t/\tau_j) = \sum_j \frac{Q_j}{\tau_j} \exp(-t/\tau_j) \end{aligned}$$

I_{mj} - peak current of the j-th component.

τ_j - decaytime of the j-th component.

$Q_j = I_{mj} \cdot \tau_j$ - total charge of the j-th component.

The following definitions are used:

$\rho_j \equiv Q_j/Q$ --- charge-ratio of the j-th component.

$Q = \sum_j Q_j$ --- total charge per pulse. } (A1-9)

$\sum_j \rho_j \equiv 1.$

The solutions for the individual components are given by Equations A1-2, 3, and 4. The complete solution is obtained by superposition of the solutions for the individual components:

$$e(s) = \frac{Q}{C} \sum_j \rho_j \cdot F_j(s)$$

$$e(t) = \frac{Q}{C} \cdot f(t) \quad \} \quad (A1-10)$$

$$f(t) = \sum_j \rho_j \cdot f_j(t)$$

The decay times and the relative ratios of the individual current-components are known from experimental data for most scintillation materials. Usually only two components are necessary to describe the scintillation decay with sufficient accuracy. Even in this case, solutions to Equations A1-10 can be obtained only by numerical methods. For stilbene and some liquid scintillators, a large ratio between the two decay times is found and further simplifications are possible.

4. TWO-COMPONENT SCINTILLATION PULSE

The following assumptions are made:

(a) The initial decay (fast component, τ_f) is short enough to be neglected. An error of the order of τ_f is thereby introduced in calculations involving the shape of the time function.

(b) Only one other component (slow component, τ_s) is considered.

The time-function, resulting from the slow component, is given by Equation A1-4. For the fast component, a step-response with an exponential decay determined only by the integration time constant can be assumed:

$$\tau_f \ll t, T : f_f(t) = \exp(-t/T)$$

The following normalizations are used:

$$\tau_f \rightarrow 0, \tau_s \equiv \tau;$$

$$\begin{aligned} \rho_f + \rho_s = 1 : \quad \rho &\equiv \rho_s \\ 1 - \rho &\equiv \rho_f \end{aligned} \quad \} \quad (A1-11)$$

With above parameters the complete time-function is the following:

$$f(t) = (1 - \rho) f_f(t) + \rho \cdot f_s(t).$$

Substituting the appropriate functions from previous equations, we obtain:

$$f(t) = \frac{x}{x-1} [M \cdot \exp(-t/T) - \rho \cdot \exp(-t/\tau)]$$

$$f(0) = 1 - \rho \quad \} \quad (A1-12)$$

$$M \equiv 1 - \frac{1-\rho}{x} \quad - - - \text{auxiliary parameter.}$$

By definition, the time-function is identical to zero for negative times; a discontinuity is therefore introduced at zero time. A maximum at times other than zero is obtained only if the slope of the time-function at zero time is positive:

$$f'(0_+) > 0 : t_M > 0$$

$$f'(0_+) \leq 0 : t_M \equiv 0$$

$$\} \quad (A1-13)$$

$$f'(0_+) = \frac{\rho}{\tau} - \frac{1-\rho}{T}$$

The time of the maximum (t_M) and the maximum value of $f(t)$ can be obtained by differentiation of Equation A1-12, but a closer examination of that equation reveals simpler relations. Formally, the zero crossing time (t_r) of the function described by Equation A1-12 is obtained:

$$f(t_r) = 0 : \frac{t_r}{\tau} = \frac{x}{x-1} \ln \frac{\rho}{M}$$

$$\} \quad (A1-14)$$

$$\frac{t_r}{\tau} \leq 0$$

A translation of the time-function $f(t)$ by an amount of t_r yields the following result:

$$t \rightarrow t + t_r :$$

$$f(t + t_r) = M \cdot \left(\frac{\rho}{M}\right)^{\frac{1}{1-x}} \cdot \frac{x}{x-1} [\exp(-t/T) - \exp(-t/\tau)] \quad (A1-15)$$

Except for a time-independent multiplier, this function is identical to the time function obtained for a single component (Eq. A1-4). The results of the corresponding case for only one component can therefore be modified in a simple manner to obtain the maximum of the time function resulting from two components:

(a) The maximum occurs earlier by the amount of t_r .

(b) The value of the maximum is found by multiplying the corresponding values obtained for the one-component case by a factor depending on the time constant ratio, x , and the charge ratio, ρ , only.

These relations are illustrated in Figure A1-1 for one particular choice of x and ρ ($x = 5$, $\rho = 0.8$). For the maximum, the following values are obtained:

$$f_M = M \cdot \left(\frac{\rho}{M}\right)^{\frac{1}{1-x}} \cdot x^{\frac{1}{1-x}} = (\rho x)^{\frac{1}{1-x}} \cdot M \quad \} \quad (A1-16)$$

$$t_M/\tau = \frac{x}{x-1} \ln x - |t_r/\tau| = \frac{x}{x-1} \ln \frac{x\rho}{M}$$

For $\rho = 1$ ($M = 1$) all relations reduce to a form obtained for the one-component case. Considering several kinds of exiting radiation, it is found that only the charge-ratio depends on the nature of the radiation (Ref. 2).

Under these conditions, the pulse shape of the signal is dependent only on the charge ratio, ρ , and therefore the pulse shape contains information on the nature of the exiting radiation. By differentiating the previous equations with respect to ρ , shape-sensitivity parameters are obtained:

$$\left. \begin{aligned} \frac{d}{d\rho} f_M &= - \frac{1-\rho}{x} \cdot \frac{1}{\rho M} \cdot f_M \\ \frac{d}{d\rho} \left(\frac{t_M}{\tau} \right) &= \frac{1}{\rho M} \end{aligned} \right\} \quad (A1-17)$$

For two kinds of radiation, described by the charge ratios ρ_a and ρ_b , the following relations between the maximum pulse heights corresponding to each radiation are obtained:

$$t_{Ma}, t_{Mb} > 0 :$$

$$\left. \begin{aligned} \frac{f_{Ma}}{f_{Mb}} &= \left(\frac{\rho_a}{\rho_b} \right)^{\frac{1}{1-x}} \cdot \left(\frac{M_a}{M_b} \right)^{\frac{x}{x-1}} \end{aligned} \right\} \quad (A1-18)$$

$$\frac{t_{Mb}}{\tau} - \frac{t_{Ma}}{\tau} = \frac{x}{x-1} \ln \frac{\rho_b M_a}{\rho_a M_b}$$

The pulse height ratio depends on the integration time constant, T ($x = T/\tau$). Subsequent shaping operations, either of the RC - or delay line -type, also influence this ratio.

Analogous to the one-component case, the following approximations are obtained:

4.1 Nearly Ideal Integration of the Slow Component, $x \gg 1$,

$$\underline{T \gg \tau}$$

$$f(t) = \exp(-t/T) - \rho \exp(-t/\tau)$$

$$M \doteq 1, \quad t_r \doteq \ln \rho$$

$$t_M/\tau = \ln \rho x$$

$$\frac{d}{d\rho} \left(\frac{t_M}{\tau} \right) = \frac{1}{\rho} \quad \} \quad (A1-19)$$

$$f_M \doteq 1 - \frac{1}{x} \doteq 1$$

$$\frac{d}{d\rho} f_M \doteq 0$$

For two kinds of radiation, we obtain the following relations:

$$\frac{f_{Ma}}{f_{Mb}} \doteq 1$$

$$\frac{t_{Mb}}{\tau} - \frac{t_{Ma}}{\tau} = \ln \frac{\rho_b}{\rho_a} \quad \} \quad (A1-19a)$$

$$(t_{Ma}, t_{Mb} > 0)$$

4.2 Optimum Signal-To-Noise Ratio for the slow component, $x = 1$,

$$\underline{T = \tau}$$

The solutions for this case are obtained from Equation A1-6:

$$f(t) = (1 - \rho + \rho \cdot \frac{t}{\tau}) \exp(-t/\tau)$$

$$f(0) = 1 - \rho$$

$$f'(0_+) = \frac{2\rho - 1}{\tau}$$

$$t_r/\tau = 1 - \frac{1}{\rho} \quad \} \quad (A1-20)$$

$$t_M/\tau = 2 - \frac{1}{\rho}$$

$$f_M = \frac{\rho}{e^2} \cdot \exp\left(\frac{1}{\rho}\right) \doteq 0.135\rho \cdot \exp\left(\frac{1}{\rho}\right)$$

Considering shape-sensitivity and two kinds of radiation,
the following relations are found:

$$\frac{d}{d\rho} f_M = - \frac{1 - \rho}{\rho^2} \cdot f_M$$

$$\frac{d}{d\rho} \left(\frac{t_M}{\tau}\right) = \frac{1}{\rho^2}$$

$$\frac{f_{Ma}}{f_{Mb}} = \exp\left(\frac{1}{\rho_a} - \frac{1}{\rho_b}\right) \quad \} \quad (A1-20a)$$

$$\frac{t_{Mb}}{\tau} - \frac{t_{Ma}}{\tau} = \frac{1}{\rho_a} - \frac{1}{\rho_b}$$

$$(t_{Ma}, t_{Mb} > 0)$$

A maximum at times different from zero is only obtained for charge-ratios of greater than 0.5:

$$|t_T| \leq \tau : \rho \geq 0.5$$

$$\rho = 0.5 : t_M = 0$$

$$F_M = \rho$$

} (A1-21)

4.3 No Integration of The Slow Component, $x \ll 1$, $T \ll \tau$

From previous equations the following results are obtained:

$$f(t) = \rho x \cdot \exp(-t/\tau) - Mx \cdot \exp(-t/T)$$

$$F(0) = 1 - \rho$$

$$t_M/\tau = -x \ln \frac{\rho x}{M}$$

A maximum at time other than zero is obtained under the following conditions:

$$\rho > 1 - x.$$

This case is of limited practical value for applications requiring pulse-shape discrimination.

5. SCINTILLATION-DECAY PROPERTIES OF STILBENE

The experimental data, obtained by R. B. Owen (Ref. 2), K. Peuckert (Ref. 3), and G. Alter and A. Coche (Ref. 4), are summarized and compared in the table below:

A and B represent the relative peak-currents associated with the fast (τ_f) and slow component (τ_s) of the fluorescence decay. The decay-times

are given in units of ns. Q_f , Q_s , and $Q = Q_f + Q_s$ are listed in relative units, the charge ratio, ρ , is obtained as the ratio between Q_s and Q .

	R. B. Owen		K. Peuckert			Walter & Coche		
Particle:	e	p	e	p	α	e	p	α
A	100	100	100	100	100	100	100	100
B	8	11	6.6	7	32	8	22	31
τ_f	6.2	6.2	5.6	6	6.2	(6.6)	(6.6)	(6.6)
τ_s	370	370	49	67	65	400	400	400
Q_f	6.2	6.2	5.6	6	6.2	6.6	6.6	6.6
Q_s	29.6	40.7	3.23	4.69	20.8	24.0	88.0	124.0
Q	35.8	46.9	8.8	10.7	27.0	30.6	94.6	130.6
ρ	0.827	0.868	0.367	0.438	0.770	0.784	0.930	0.949

Relatively good agreement can be observed for the current ratios. On the other hand, the quoted decay-times show large differences, probably due to the fact that the scintillation decay of stilbene cannot be adequately approximated by only two exponential components (Ref. 5). The pulse shape parameters, listed in above table, are useful in obtaining estimates of expected pulse shapes, keeping in mind that these data constitute only approximations.

A more accurate presentation of the scintillation decay properties of stilbene is given by Figure A1-2, where experimental data obtained by Bollinger and Thomas (Ref. 5) are shown on logarithmic scales. For comparison, the function resulting from a single exponential component of 100 ns decay-time is also shown.

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APPENDIX 2

TIMING ERROR AND DISPERSION FOR A FIXED ENERGY THRESHOLD TRIGGER

The voltage pulse, delivered by a radiation transducer, is assumed to be of the form described by the equation:

$$e(t) = e_{\max} [1 - \exp(-t/\tau)] \quad (\text{A2-1})$$

where $e_{\max}$ is proportional to energy, and τ is the decay time of the scintillator. Perfect integration is assumed.

A trigger device with a fixed threshold of e_1 ($e_1 \leq e_{\max}$) will produce an output pulse at a time $t = t_1$ when the input voltage $e(t)$ is equal to the trigger threshold e_1 :

$$e(t_1) = e_1 : t_1/\tau = -\ln(1 - \frac{e_1}{e_{\max}}). \quad (\text{A2-2})$$

The reference time, t_1 , is therefore a function of both the pulse height ($e_{\max}$) and risetime (τ) of the detector pulse.

If the pulse height exhibits statistical fluctuations, the trigger time, t_1 , will also be affected. Introducing the fundamental relation between the dispersions associated with the two quantities (Ref. 1),

$$\frac{D_{e_{\max}}}{D_{t_1}} = \left(\frac{de}{dt} \right)_{t=t_1}^2 \quad (\text{A2-3})$$

differentiating Equation A2-1,

$$\frac{de}{dt} = \frac{e_{\max}}{\tau} \exp(-t/\tau) \quad (\text{A2-4})$$

and letting $t = t_1$,

$$\left. \frac{de}{dt} \right|_{t = t_1} = \frac{e_{\max}}{\tau} \cdot \left(1 - \frac{e_1}{e_{\max}}\right) \quad (\text{A2-5})$$

the following relation is obtained:

$$\frac{\sqrt{D_{t_1}} / \tau}{\sqrt{D_{e_{\max}}} / e_{\max}} = \left(1 - \frac{e_1}{e_{\max}}\right)^{-1} \quad (\text{A2-6})$$

The definition of dispersion and its relation to resolution as commonly defined in nuclear measurements (See Appendix 5) is given by following relations (Ref. 1):

$$D_x \equiv \sigma_x^2 \quad (\text{A2-7})$$

$$r_x \equiv 2.354 \frac{\sqrt{D_x}}{x_{\text{mean}}} \quad (\text{A2-8})$$

where D_x , σ_x , and r_x are the dispersion, the standard deviation, and the resolution associated with the general statistical variable x .

The same derivations can be repeated for a detector pulse shape approximated by a linear ramp function:

$$\left. \begin{aligned} 0 \leq t \leq \tau : e(t) &= \frac{e_{\max}}{\tau} \cdot t \\ \tau \leq t \leq \infty : e(t) &= e_{\max} \end{aligned} \right\} \quad (\text{A2-9})$$

The corresponding results are:

$$t_1 / \tau = e_1 / e_{\max} \quad (\text{A2-10})$$

$$\frac{\sqrt{D_{t1}} / \tau}{\sqrt{D_{e_{max}}} / e_{max}} = 1 \quad (\text{A2-11})$$

Analogous to the energy resolution, a timing resolution for the trigger time, t_1 , may be defined:

$$r_e = 2.354 \frac{\sqrt{D_{e_{max}}}}{e_{max}} = \frac{W_{e_{max}}}{e_{max}} \quad (\text{A2-12})$$

$$r_{t1} = 2.354 \frac{\sqrt{D_{t1}}}{\tau} = \frac{W_{t1}}{\tau} \quad (\text{A2-13})$$

$W_{e_{max}}$ and W_{t1} represent the full width at half-maximum of the distributions of e_{max} and t_1 . Introducing these relations, we obtain from previous equations (Equations A2-2 and A2-10 are restated for convenience):

Exponential pulse:

$$\begin{aligned} t_1/\tau &= -\ln \left(1 - \frac{e_1}{e_{max}} \right) \\ r_{t1}/r_e &= \frac{1}{1 - e_1/e_{max}} \end{aligned} \quad \} \quad (\text{A2-14})$$

Linear ramp:

$$\begin{aligned} t_1/\tau &= \frac{e_1}{e_{max}} \\ r_{t1}/r_e &= 1 \end{aligned} \quad \} \quad (\text{A2-15})$$

The dependence of trigger time and trigger time resolution on the threshold ratio $e_1/e_{\max}$ is shown in Figure A2-1 for both pulse shapes.

For a fixed threshold (e_1), the timing error ($\Delta t_1 = t_{1a} - t_{1b}$) and the timing resolution (r_{t1}) can be found for any given pulse height range ($e_a \leq e_{\max} \leq e_b$), if the risetime and energy resolution of the energy pulses are known.

Reference:

Jungclausen, H.: N.I.M.27(1964) p 88-92.

APPENDIX 3

ZERO-CROSSING TIMES FOR DELAYLINE SHAPING

The signal pulses, obtained from a scintillation counter, are of a shape uniquely determined by the scintillation material, the integration time constant, and the kind of radiation incident on the scintillator (Appendix 1). After passing these signals through a differentiation network, pulses are obtained which cross the zero-level at times dependent only on the shape of the original pulses. The zero-crossing times are independent of pulse-height (energy) and contain information necessary to sort the signals originating from different kinds of radiation.

The following normalized parameters are used (Ref. 1):

$$\begin{aligned} x &= T/\tau \\ y &= T_d/\tau \\ z &= t/\tau \end{aligned} \quad \} \quad (A3-1)$$

τ - decay time of the fluorescence radiation of the scintillator.

T - time constant of the charge-to-voltage conversion network.

T_d - time constant of the differentiation network.

Only delayline shaping will be considered. T_d is then the time-delay of the delaylines. Additional shaping operations (integration, band-pass limitations) and statistical influences (fluctuations, timing dispersion) are not included in the following analysis.

The time function derived in Appendix 1 (two-component decay) is used to represent the pulse-shape before differentiation:

$$\begin{aligned}
 z < 0 : f(z) &= 0 \\
 z \geq 0 : f(z) &= \frac{x}{x-1} \left[M \exp\left(-\frac{z}{x}\right) - \rho \exp(-z) \right]
 \end{aligned}
 \tag{A3-2}$$

1. SINGLE DELAYLINE SHAPING

This operation is represented by the transfer-function

$$F(s) = 1 - \exp(-sTd)$$

and the following time function is obtained for the output pulse:

$$f_{D1}(z) = f(z) - f(z-y).$$

The pulse given by the above equation crosses the zero-level at a time for which the magnitudes of the input pulse and the delayed pulse are equal (Figure A3-1):

$$\begin{aligned}
 z = z_0 : f_{D1}(z_0) &= 0 \\
 f(z_0) &= f(z_0 - y)
 \end{aligned}$$

From Equation A3-2 the following results are obtained:

$$\begin{aligned}
 z_0 &\geq y \\
 z_0 &= \frac{x}{x-1} \left[\ln \frac{\rho}{M} + \ln D_1 \right] \\
 D_1 &= \frac{1 - \exp(y)}{1 - \exp(y/x)} \\
 \frac{dz_0}{d\rho} &= \frac{1}{\rho M}
 \end{aligned}
 \tag{A3-3}$$

A non-trivial solution ($z_0 \neq y$) is obtained only in the range of $y < z_1$, where z_1 is the time at which the input pulse assumes again the

initial value $f(0) = f(z_1) = 1 - \rho$ (see Figure A3-1). Within this range the difference of the zero-crossing times associated with two kinds of radiation is independent of the shaping parameter, y :

$$z_{oa} \neq y, z_{ob} \neq y:$$

$$z_{ob} - z_{oa} = \frac{x}{x-1} \ln \frac{\rho_b M_a}{\rho_a M_b} \quad (A3-4)$$

The same relation is obtained for the maxima of the input pulses (Appendix 1). In pulse shape discrimination systems based on zero-crossing time differences, the differences themselves are not the only performance-criteria for separation. Another important factor is the accuracy with which the zero-crossing times can be determined experimentally. This accuracy in turn depends on the rate at which the shaped signals cross the zero-level (Ref. 1). While this problem is not considered here, a qualitative estimate of the timing accuracy and dispersion of the zero-crossing signals can be obtained by visual inspection of the intersect of the original signal and the delayed signal (Figure A3-1): The slope of the shaped signal at zero-crossing time is related to the angle at which the two signals intersect. A larger angle results in greater accuracy and smaller dispersion of the zero-crossing signal.

Analogous to Appendix 1 the following approximations are obtained:

1.1 Nearly ideal integration of the slow component, $x \gg 1$,

$T \gg \tau$:

For $x \rightarrow \infty$ no zero-crossing is obtained. For other cases, the zero-crossing is the following ($M \doteq 1$):

$$z_0 \doteq \ln \rho + \ln D_1 \quad (\text{A3-5})$$

a. $y \ll 1, y/x \ll 1 : D_1 \doteq x$

$$z_0 = \ln \rho x = z_M$$

In regard to timing accuracy this case is not desirable (creeping zero-crossing).

b. $y \gg 1, y/x \ll 1 : D_1 = \frac{x}{y} \exp(y)$

$$z_0 - y = \ln \frac{\rho x}{y} = z_M - \ln y.$$

1.2 Optimum Signal-to-noise ratio for the slow component, $x = 1$,

$T = \tau$:

The solution for this case is obtained by substitution of the appropriate time function from Appendix 1 into the zero-crossing relation:

$$z_0 - y = 1 - \frac{1}{\rho} + y \frac{1}{\exp(y) - 1} \quad (\text{A3-6})$$

a. $y \ll 1 : z_0 - y = 2 - \frac{1}{\rho}$

No solution $z_0 \geq y$ is obtained for $\rho < 0.5$.

b. $y = 1 : z_0 - y = \frac{e}{e-1} - \frac{1}{\rho}$

No solution $z_0 > y$ is obtained for $\rho < 0.632$.

c. $y \gg 1$: For this case, y is usually larger than z_1 and the trivial solution $z_0 - y = 0$ is obtained.

The third approximation ($x \ll 1$, no integration of the slow component) is of little practical interest: The pulse duration is very short and the zero-crossing time is equal to the delay time.

2. DOUBLE DELAYLINE SHAPING

Only the shaping operation with 2 identical delaylines is considered ($T_{d1} = T_{d2} = T_d$). The transfer function of this shaping operation,

$$F(s) = [(1 - \exp(-sT_d))^2$$

yields the following time function:

$$f_{D2}(z) = f(z) - 2 f(z-y) + f(z-2y)$$

Again all functions are identical to zero for negative arguments. With this restriction the following zero-crossing time relation is obtained (Figure A3-1):

$$z = z_0: f_D(z_0) = 0$$

$$f(z_0) = 2 f(z_0 - y)$$

$$y \leq z_0 \leq 2y$$

The solution is the following:

$$z_0 = \frac{x}{x-1} [\ln \rho + \ln D_2]$$

$$D_2 = \frac{1 - 2 \exp(y)}{1 - 2 \exp(y/x)} \quad \} \quad (A3-7)$$

$$\frac{d}{d\rho} z_0 = \frac{1}{\rho M}$$

For two kinds of radiation, we find again the same relation between the zero-crossing times as before. Non-trivial solutions are obtained only in the range $z_{21} < y < z_{22}$ (Figure A3-1). Generally it can be observed that for any shaping parameter y the shaped signal crosses the zero-level at faster rate than in the case of single delayline shaping (Figure A3-1). Approximations for special cases are considered next:

2.1 Nearly ideal integration of the slow component, $x \gg 1$,

$T \gg \tau$

The previous equation reduces to the following:

$$z_0 = \ln \rho + \ln D_2 \quad (\text{A3-8})$$

a. $y \ll 1, y/x \ll 1 : D_2 \doteq \frac{1 + 2y}{1 + 2y/x}$

$$z_0 - y = \ln \rho + y$$

b. $y \gg 1, y/x \gg 1$: For this case, y is usually larger than z_{22} and the zero-crossing time is equal to the delaytime ($z_0 - y = 0$).

c. $y \gg 1, y/x \ll 1 : D_2 = \frac{2 \exp(y)}{1 + 2 y/x}$

$$z_0 - y = \ln \rho + \ln 2 - 2 y/x$$

d. $\rho = 1, x \rightarrow \infty$: single component decay with perfect integration

$$y \gg 1 : z_0 - y = \ln 2$$

$$y \ll 1 : z_0 - y = y$$

2.2 Optimum signal-to-noise ratio for the slow component, $x = 1$,

$T = \tau$

Again the solution is obtained by using the appropriate time function from Appendix 1:

$$z_o = 1 - \frac{1}{\rho} + y + y \frac{1}{2 \exp(y) - 1} \quad (\text{A3-9})$$

$$(a) \quad y \ll 1 : z_o - y = 1 - \frac{1}{\rho} + y$$

$$(b) \quad y = 1 : z_o - y = \frac{2e}{2e - 1} - \frac{1}{\rho}$$

$$(c) \quad y \gg 1 : z_o - y = 1 - \frac{1}{\rho} + 2y \exp(-y)$$

$$(d) \quad \rho = 1 : \text{single component decay}$$

$$y \gg 1 : z_o - y = 0$$

$$y \ll 1 : z_o - y = y$$

The third approximation ($x \ll 1$, no integration of the slow component) is again of little practical use for pulse-shape discrimination purposes.

3. TRIPLE DELAYLINE SHAPING

Assuming identical delaylines the shaping operation is represented by the following transfer function:

$$F(s) = [1 - \exp(-sTd)]^3$$

The shaped pulse exhibits two zero-crossings and is therefore of interest in timing applications. The relation between the two zero-crossing times will be illustrated for one particular case only ($x \rightarrow \infty$, $y \gg 1$). The following time function applies:

$$\left. \begin{aligned} f(z) &= 1 - \rho \cdot \exp(-z) \\ f_M &\rightarrow 1, \quad z_M \rightarrow \infty \end{aligned} \right\} \quad (\text{A3-10})$$

Under these conditions the two zero-crossing times are:

(a) First Zero-crossing:

$$f(z_{01} - y) = \frac{1}{3}$$

$$z_{01} - y = \ln \rho + \ln \frac{3}{2} \quad (\text{A3-11a})$$

(b) Second Zero-crossing:

$$f(z_{02} - 2y) = \frac{2}{3}$$

$$z_{02} - 2y = \ln \rho + \ln 3 \quad (\text{A3-11b})$$

$$z_{02} - z_{01} = \ln 2 + y \quad (\text{A3-11c})$$

Considering two kinds of radiation yielding pulse shapes as outlined in Appendix 1, no information on the type of radiation is contained in the time difference of the two zero-crossings. However, if the pulse shapes originating from two kinds of radiation cannot be approximated using an identical decay constant and different charge ratios, the zero-crossing time differences (Equation A3-11c) is dependent on the decaytime ($z = t/\tau$) and this time-difference can be used to discriminate between types of incident radiation.

Reference:

1. Fulle, R., Mathe, G. and Netzband, D. - N.I.M. 35 (1965) 250-260.

APPENDIX 4

DELAY GENERATOR

The delay of a logic pulse is a function often required in nuclear instrumentation. Continuous adjustment and direct reading of the delay is desirable. For delay times exceeding about one hundred nanoseconds this function can be performed by conventional monostable generators. Some problems associated with the use of semiconductors are discussed by DeLotto (Ref. 1). The low reverse breakdown voltage of the emitter-base junctions of fast transistors imposes limitations on the maximum amplitude of timing waveforms which can be used in semiconductor circuits. This limitation was removed by the use of a "disconnect" diode (D4) which limits the voltage excursion on the base of Q_1 (Figure A4-1, Figure 12) to a safe value without affecting the timing waveform (Ref. 2). This can also be accomplished by the use of two diodes connected in series with the emitters of Q_1 and Q_2 , but results in lower regenerative gain during the transistions between the stable and quasi-stable states and is therefore not to be recommended.

The delay time control and recovery properties of the delay generator under discussion ($\Delta 02$, Figure A4-1, also Figure 12) can be obtained from the waveforms shown in Figure A4-2:

Upon triggering the delay period at a time $t = 0$, the collector voltage of Q_1 drops to a level established by the control voltage, E_c . This voltage step is impressed on the timing capacitor, C_T , which then begins to discharge through R_T towards the voltage level E_B with a time constant of $\tau = R_T C_T$. As soon as this voltage reaches the value necessary to turn on transistor Q_2 , the delay period is terminated and an output pulse is derived

from the negative going edge of the waveform on the collector of Q_2 .

The delay period (T_{Do}) is obtained from the following relations:

Exponential discharge, normalized:

$$y = 1 - \exp(-t/\tau)$$

$$y = y_o : t = T_{Do}, \quad \} \quad (A4-1)$$

$$T_{Do}/\tau = -\ln(1 - y_o)$$

Neglecting the voltage drop across forward biased semiconductor junctions, we obtain (Figure A4-2):

$$y_o = \frac{\Delta E_o}{\Delta E_o + E_B} = \frac{\alpha E_1}{\alpha E_1 + E_B} = \frac{r\alpha}{1 + r\alpha}$$

$$T_{Do}/\tau = \ln(1 + r\alpha) \quad \} \quad (A4-2)$$

α represents the fraction of E_1 which is used to control the timing function (E_c). For a linear control potentiometer, α is directly proportional to the dial reading, since by the use of an emitter follower (Q_4) loading effects on the control potentiometer are eliminated. The function described by Equation A4-2 is included in Figure A4-3.

Examination of the timing equation (A4-2) shows that the delay period (T_{Do}) for any selected delay ($\alpha = \text{constant}$) is sensitive only to the ratio (r) between the two positive supply voltages. If the circuit as shown in Figure 10 is used ($r \equiv 1$), or if the timing resistor, R_T , is returned to the voltage E_1 instead of E_B , the delay period becomes insensitive to supply voltages.

Upon termination of the delay period, the voltage on the collector of Q_1 returns toward E_B with a time constant of $\tau_R = R_C C_C$ until the quiescent level (E_1) is reached. This time is the recovery period of the monostable generator. If the generator is triggered again during this period, the voltage step available for transfer to the timing capacitor will be smaller ($\Delta E_1 \leq \Delta E_0$), resulting in a shorter delay period ($T_{D1} \leq T_{D0}$). The relations, illustrated in Figure A4-2, are described by the following equations:

Waveform on collector of Q_1 :

$$y = 1 - \exp(-t'/\tau_R)$$

$$t' = t - T_{D0}$$

$$t' = t_1 : y = y_1$$

$$\frac{\Delta E_1}{\Delta E_0} = y_1/y_0 = 1 - \exp(-t_1/\tau_R) \quad \} \quad (A4-3)$$

$$0 \leq t_1 \leq T_R$$

With $\Delta E_0 = \alpha E_1$ we obtain:

$$\Delta E_1 = \alpha E_1 [1 - \exp(-t_1/\tau_R)] = \alpha_1 E_1$$

α_1 ($\alpha_1 \leq \alpha$) indicates formally a selection of a shorter delay period. Using Equation A4-2, we obtain:

$$\exp(T_{Do}/\tau) = 1 + r\alpha$$

$$\exp(T_{D1}/\tau) = 1 + r\alpha [1 - \exp(-t_1/\tau_R)]$$

$$T_{D1} - T_{Do} = -\Delta T_{D10} :$$

$$\exp\left(-\frac{\Delta T_{D10}}{\tau}\right) = 1 - \frac{r\alpha}{1 + r\alpha} \exp(-t_1/\tau_R)$$

$$\frac{\Delta T_{D10}}{\tau} \ll 1 :$$

$$\frac{\Delta T_{D10}}{\tau} \doteq \frac{r\alpha}{1 + r\alpha} \exp(-t_1/\tau_R) \quad (A4-4)$$

$$x = \frac{T_{D1}}{T_{Do}} = 1 - \frac{\Delta T_{D10}}{T_{Do}} = 1 - \frac{r\alpha}{1 + r\alpha} \cdot \frac{1}{\ln(1+r\alpha)} \exp(-t_1/\tau_R)$$

$$x = 1 - a \cdot \exp(-t_1/\tau_R) \doteq 1 - \exp(-t_1/\tau_R)$$

x : normalized delay period.

a : circuit parameter.

The above equation describes the delay defect as observed on the original version of the delay generator ($r = 1$, Figure 14). The timing error decreases rapidly with increasing pulse spacing but, theoretically, an infinite recovery time is obtained. For the version as shown in Figure A4-1 a timing error is only possible for the limited time interval $0 \leq t' \leq T_R$ ($T_{Do} \leq t_1 \leq T_{Do} + T_R$).

The total recovery period (T_R) can be obtained from Equations A4-3:

$$y = y_0: t' = T_R$$

$$T_R/\tau_R = - \ln (1 - y_0)$$

$$\text{With } y_0 = \frac{\alpha E_1}{(1-r)E_B + \alpha E_1} = \frac{r\alpha}{1-r + r\alpha}$$

we obtain

$$T_R/\tau_R = \ln(1 + \frac{r}{1-r} \cdot \alpha) \quad (\text{A4-5})$$

For the supply voltage ratio of $r = \frac{1}{2}$ the relation reduces to

$$T_R/\tau_R = \ln (1 + \alpha) \quad (\text{A4-6})$$

Again Figure A4-3 can be used to estimate the recovery time, provided τ_R is known.

For pulses arriving at random, the timing error needs to be considered. B. Soucek (Ref. 3) investigated circuits with recovery properties described by Equation A4-4 and by assuming a Poisson-distribution for the input pulses, he obtained the following distribution function for the resulting delay times:

$$\begin{aligned} g(x) &= n (1-x)^{n-1} \\ n &= \frac{N \cdot \tau_R}{a} \quad \text{--- rate dependent parameter} \\ x &= \frac{T_{D1}}{T_{Do}}, \quad 0 \leq x \leq 1 \quad \text{--- normalized delay time} \\ a &\doteq 1 \quad \text{--- circuit parameter} \\ N &\text{--- mean input rate.} \end{aligned} \quad \} \quad (\text{A4-7})$$

From the above relations the probability of not exceeding a certain delay error can be calculated:

$$P(x_0 \leq x \leq 1) = \frac{\int_{x_0}^1 g(x) \cdot dx}{\int_0^1 g(x) \cdot dx} = (1 - x_0)^n$$

$$n = \frac{\ln P(x_0 \leq x \leq 1)}{\ln (1 - x_0)} \quad (A4-8)$$

The count-rate, satisfying any selection of P and x_0 is:

$$N(P, x_0) = \frac{a}{\tau_R} \cdot \frac{\ln P(x_0 \leq x \leq 1)}{\ln (1 - x_0)} \quad (A4-9)$$

Definitions:

$P(x_0 \leq x \leq 1)$: Probability of obtaining delay periods in the range $x_0 \leq x \leq 1$.

x_0 : minimum acceptable normalized delay period, determined by the maximum acceptable timing error.

$\frac{\Delta T_{D10}}{T_{Do}} = 1 - x_0$: maximum acceptable timing error.

$N(P, x_0)$: maximum permissible count rate consistent with the above requirements.

Equation A4-9 applies to a circuit with infinite recovery time, $T_R \rightarrow \infty$, and exponentially diminishing timing error. For the circuit of Figure A4-1 this condition is satisfied for $r \equiv 1 (E_1 \equiv E_R)$. Usually probabilities close to one are required for the "correct" delay period and equation A4-9 can be simplified by series expansion of the numerator:

$$\ln P = \ln (1 - \epsilon) \doteq - \epsilon$$

$$N (\epsilon, x_o) \doteq \frac{a}{\tau_R} \cdot \frac{\epsilon}{K}$$

} (A4-10)

$$K = K (x_o) = - \ln (1 - x_o)$$

ϵ : Fraction of pulses associated with a timing error of greater than x_o .

The circuit parameter, a , shows weak dependence on α and can be neglected ($a \doteq 1$, see Figure A4-3). The variable K is listed below:

$\frac{\Delta T_{D10}}{T_{Do}} = 1 - x_o$	10^{-2}	10^{-3}	10^{-4}	10^{-5}
$K(x_o) = - \ln(1-x_o)$	4.6	6.9	9.2	11.5

For reasonable timing errors (less than 1%) only a mild influence of K on the permissible count rate can be observed. However, the maximum permissible count rate is strongly dependent on the recovery time constant, τ_R , and the fraction of pulses permitted to have a timing error, ϵ .

This is shown in the following example:

$$T_{Do} = 1400 \text{ ns}$$

$$\Delta T_{D10} = 1.4 \text{ ns}, \quad \frac{\Delta T_{D10}}{T_{Do}} = 10^{-3}, \quad K = 6.9;$$

$$\tau_R = 0.54 \text{ } \mu\text{s}, \text{ obtained from Figure 14;}$$

$$N (\epsilon, 10^{-3}) \doteq 0.27 \times 10^6 \times \epsilon \text{ pps.}$$

The maximum count rates, for which 10, 1, and 0.1 percent of the pulses show a timing error of 1.4 ns or more, become 27,000, 2700, and 270 pulses per

second. If the timing accuracy requirement is relaxed by a factor of 10, the corresponding count rates increase only by a factor of 1.5. Improved performance at higher count rates can be obtained only by a drastic reduction of the recovery time constant.

A circuit having a limited recovery period (T_R , eq. A4-6) can be analyzed only with difficulty using the approach of Reference 3. Usually the error distribution is not of interest and the fraction of pulses associated with an error can be obtained by applying Poisson-statistics to the total recovery interval:

$$\begin{aligned} P_m(U) &= \frac{U^m}{m!} \exp(-U) \\ P_0(U) &= \exp(-U) \end{aligned} \quad (A4-11)$$

$P_m(U)$: probability of finding exactly m events in any time interval t .

$P_0(U)$: probability of finding exactly zero events in any time interval t .

$U = Nt$, N : mean event rate.

For events occurring in the time interval $t = T_R$, the delay generator will exhibit timing errors: outside this recovery interval, the timing errors are zero. Therefore following the interpretation is applicable:

Fraction of pulses not in the recovery interval and therefore having no timing error associated with it:

$$N' = N(1 - \epsilon) = N \cdot P_0(U)$$

ϵ represents the fraction of pulses in the recovery interval and is therefore equivalent to the definition of Equation A4-10. Using the

same approximations ($\epsilon \ll 1$), we obtain

$$N \doteq \frac{\epsilon}{T_R} \quad (A4-12)$$

More generally, N can now be interpreted as the maximum permissible event rate causing a fraction ϵ of erroneous outputs in a device having a recovery time of T_R .

For the circuit shown in Figure A4-1 the following recovery times are measured:

$$T_{Do} = 1.5 \text{ } \mu\text{s}; T_R \leq 0.4 \text{ } \mu\text{s}$$

$$N = 2.5 \times 10^6 \times \epsilon$$

The resulting count rates are 250,000, 25,000; and 2,500 pulses per second using the same error fractions as in the previous example. Modifying the random input rate of the delay generator by a circuit with a dead-time of $T_{Do} + T_R$ removes all count rate dependent timing errors. Making use of the general definition of N and ϵ above, the fractional counting loss of such a combination can be obtained from A4-12:

$$\epsilon \doteq N (T_{Do} + T_R) \quad (A4-13)$$

References:

1. DeLotto, I. - Nuclear Electronics Vol II (Belgrade 1961)
IAEA, Vienna, 1962.
2. Karlin, R. A. - Electronic Design Jan. 4, 1965, p58-61.
3. Soucek, B. - NIM 29 (1964) 109-114.

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APPENDIX 5

RESOLUTION MEASURES

For monoenergetic particles striking a nuclear radiation transducer, the resolution is usually defined as the ratio of the observed linewidth to the probable amplitude of the line:

$$r = \frac{W_A}{A_O}, R = r \cdot 100 \text{ (\%)} \quad (\text{A5-1})$$

W_A : Line width, full width at half maximum.

A_O : probable, mean value of A.

The energy conversion process of particle energy into pulse amplitude is statistical and the pulse height distribution follows some probability law. Frequently, the observed amplitude distribution is close to the frequency function of the Normal Distribution (Gaussian Distribution):

$$\begin{aligned} \phi(x) &\equiv \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot \exp \left[-\frac{1}{2} \frac{(x - x_O)^2}{\sigma^2} \right] \\ \phi_u(U) &\equiv \frac{1}{\sigma} \cdot \phi_u \left(\frac{x - x_O}{\sigma} \right) \\ \phi_u(U) &\equiv \frac{1}{\sqrt{2\pi}} \cdot \exp \left[-\frac{1}{2} U^2 \right] \end{aligned} \quad (\text{A5-2})$$

Definitions:

$\phi(x)$:	frequency distribution of x
$\phi_u(U)$:	normalized frequency distribution
x_O :	mean value of x
σ :	standard deviation
σ^2 :	variance, dispersion

0.798σ :	mean deviation (m.a.e.)
0.674σ :	probable deviation (p.e.)
1.177σ :	one half width
2.354σ :	full half width (W_x)
$h = \frac{1}{\sqrt{2} \cdot \sigma}$:	precision measure
$U = \frac{x - x_0}{\sigma}$:	standardized variable.

The normal frequency function (error curve) is shown in Figure A5-1.

Experimental data with resolutions exceeding a few percent for a single line are treated in an optimum way by consideration of the tangents through the inflection points of the measured distribution (graphic manipulation):

(a) For all practical purposes these tangents are the best straight lines through the slopes of the measured distribution. The half-maxima points are located on these lines.

(b) From the intersect of these lines the mean amplitude (pulse height) is obtained.

(c) The intensity corresponding to the mean amplitude can be compared to the intensity corresponding to the tangent-intersect and a measure of approximation of the experimental data by the normal frequency function can be obtained. The same manipulations can be applied to non-symmetric distributions.

The line width as observed in nuclear spectroscopy is the result of contributions from several statistical processes (Ref. 1, 2, 3). A good performance estimate of practical radiation transducers over a wide energy

range is obtained by considering only the statistical fluctuations of the number of particles produced in the energy conversion process available for signal generation (Ref. 2, 3). Assuming a Normal Distribution, the following resolution is obtained:

$$r \doteq \frac{2.35}{\sqrt{N}} \quad (\text{A5-3})$$

N: Number of photoelectrons in a scintillation counter; number of ion-pairs in a solid state detector or ionization chamber.

For most radiation transducers N is proportional to energy or at least linear with energy over a wide energy range. The energy dependence of resolution and line width of a scintillation counter is therefore approximated by the following simple relations (Ref. 3):

$$\begin{aligned} R = 100 \cdot r &= \frac{\lambda}{\sqrt{E}} \\ W_E = r \cdot E &= \frac{\lambda}{100} \sqrt{E} \end{aligned} \quad \} \quad (\text{A5-4})$$

E: Energy loss in the scintillator.

λ : Constant depending primarily only on the scintillator.

The relation between the resolution and line width, defined for a single line, and the shapes, degraded by resolution, of certain types of continuous spectra are discussed next:

1. RECTANGULAR PULSE HEIGHT DISTRIBUTION

A typical representative of this type of spectrum is the proton recoil spectrum of hydrogen obtained from monoenergetic neutrons. The spectrum

consists of a family of single lines, each of equal intensity, and each line subjected to a broadening described by Equation A5-4. The pulse-height distribution extends from zero to a maximum pulse-height corresponding to the incident neutron energy. For the narrow pulse-height region in the vicinity of the edge, the energy dependence of the resolution can be neglected and the frequency function describing the spectrum near the edge can be obtained by integration of the frequency functions of the individual single lines:

$$\int_{-\infty}^{x_0} \phi(x_1, x_0) dx_0 = \int_x^{+\infty} \phi(x_1, x_0) dx_1 \equiv 1 - \Phi(x)$$

The result is the complement of the distribution function of the Normal Distribution previously used:

$$\Phi(x) = \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot \int_{-\infty}^x \exp\left(-\frac{1}{2} \frac{(x-x_0)^2}{\sigma^2}\right) dx \equiv \Phi_u\left(\frac{x-x_0}{\sigma}\right)$$

$$\begin{aligned} \Phi_u(U) &= \frac{1}{\sqrt{2\pi}} \cdot \int_{-\infty}^U \exp\left(-\frac{1}{2} U^2\right) du \equiv \\ &\equiv \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{U}{\sqrt{2}}\right)\right] \end{aligned} \quad \} \quad (\text{A5-5})$$

This function is also shown in Figure A5-1. It can be observed that the tangent through the inflection point (x_0) intersects the 0 and 100 percent lines at pulse heights corresponding to within 3 percent to the pulse heights associated with half maxima points of the corresponding single line. These points can therefore be used to define a resolution consistent with that of the single line obtained

for the same detector:

$$r = \frac{X_E - X_C}{X_O} \doteq \frac{W_x}{X_O} \quad (A5-6)$$

2. COMPTON ELECTRON DISTRIBUTION

The theoretical compton electron spectrum shows again a continuous pulse-height distribution from zero to a maximum pulse height corresponding to the maximum compton electron energy obtained from monoenergetic gamma radiation (Réf. 4).

Analytic treatment analogous to the rectangular distribution is nearly impossible. This case was therefore treated numerically: The theoretical shape of the compton spectrum was broadened succesively on a digital computer. For more than four broadening steps this process results in Gaussian Distributions. The number of broadening steps was controlled by observation of the resolution of a single line of energy $E_{c \text{ max}}$, subjected to the same process until the required resolution according to equation A5-4 was obtained. A λ equal to 12.5 was used (stilbene scintillator).

The result for an incident gamma energy of $E_\gamma = 2 m_o c^2 \doteq 1 \text{ MeV}$ is shown in Figure A5-2. The number of broadening steps required for this case was 8. The following results were obtained:

$E_\gamma \doteq 1 \text{ MeV}$	incident gamma energy
$E_{c \text{ max}} \doteq 0.8 \text{ MeV}$	maximum compton energy
$r = 0.139 (\lambda = 12.5)$	single line resolution
Peak:	$0.937 E_{c \text{ max}}$

Half point: $1.040 E_{c \text{ max}}$
 End point: $1.109 E_{c \text{ max}}$
 Intensity corresponding to $E_{c \text{ max}}$: 0.78. Peak intensity.

Resolution:
$$r = \frac{X_E - X_C}{X_H} = 0.140$$

The relation between the maximum compton electron energy and half-point pulse height is in good agreement with experimentally obtained relations for organic scintillators (Ref. 5). The resolution defined above gives best agreement with the analogous single line resolution (Figure A5-2). The pulse heights corresponding to X_E , X_H , and X_C can be obtained with good accuracy even from experimental data with considerable statistical fluctuations.

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FIGURE A1-1 TWO-COMPONENT SCINTILLATION DECAY

FIGURE A1-2 DECAY CHARACTERISTICS OF STILBENE

FIGURE A2-1: TIMING ERROR AND RESOLUTION
FOR FIXED THRESHOLD

WAVEFORM COLLECTOR Q_1

FIGURE A4-2 DELAY CONTROL AND RECOVERY

FIGURE A4-3 DELAY FUNCTIONS

FIGURE A5-1 NORMAL DISTRIBUTION

FIGURE A5-2 COMPTON SPECTRUM

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14. KEY WORDS	LINK A		LINK B		LINK C	
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