Neutron-Gamma Discrimination with Stilbene and Liquid Scintillators

Theory Neutrons and gammas produce light scintillation in NE-213, NE-218,* and Stilbene detectors with significantly different decay characteristics. The 10% to 90% rise time (t_R) of the integrated light from all the scintillators is approximately 130 nsec when excited with neutrons and approximately 10 nsec when excited with gamma rays.[1]** The scintillation is not a simple exponential, as is illustrated by Kuchnir and Lynch,[1] but consists of a combination of at least four components, as illustrated by their results shown in Table 1.

Table 1

SCINTILLATOR	MEAN LIFE TIME[a] (nsec)	MEAN DECAY TIME[b] (nsec)			NO. OF PHOTOELECTRONS PER keV ENERGY LOSS[c]
		τ_2	τ_3	τ_4	
Stilbene	0.1	4.05	33	270	2.3
NE 213	1.66	3.16	32.3	270	1.7
NE 213M	1.34	5.41	30.5	285	1.9
NE 218	1.76	3.58	36.5	288	2.0
Anthracene	—	—	—	—	3.6
NaI(Tl)	—	—	—	—	8.8

[a] For energy transfer from solvent to solute.
[b] First 3 components by the light output in organic scintillators.
[c] Represents loss in the scintillator when coupled to an RCA-8575 photomultiplier with good light collection.

Three parameters determine the ability to distinguish between gammas and neutrons: the total number R of photoelectrons produced at the cathode for a given energy of excitation, the shape $f(t)$ of the light scintillation for both neutrons and gammas, and the photoelectron level j at which the pulse shape information is deduced.

If one assumes that the neutron and gamma can be characterized with an effective single decay time, the probability distribution function for the jth photoelectron out of a total of R photoelectrons is given by the statistical order equation[2]

$$g(t) = \frac{R!}{(j-1)!\,(R-j)!\,\tau}\,[1 - e^{-t/\tau}]^{j-1}\,e^{-t(R-j)/\tau}\,. \qquad (1)$$

The following analysis is based on a first-order approximation of the pulse shape. If more exact results are desired, refer to the work of Kuchnir and Lynch.

Assuming an effective exponential for the scintillation permits one to obtain a better understanding of how the three parameters affect the neutron-gamma separation. The mean time for the jth photoelectron is given by[3]

$$t_j = \tau \ln \frac{R}{R-j} = \tau \ln \frac{1}{1-F}\,, \qquad (2)$$

where F is the ratio of j/R or the fraction. The variance in time of the jth photoelectrons is given by

$$\sigma_j^2 = \tau^2 \sum_{k=0}^{j} \left(\frac{1}{R-k}\right)^2 \qquad (3)$$

The width of the time distribution varies directly with τ and the photoelectron level j, but inversely with R, the total number of electrons. Therefore as the fraction at which the time information is derived increases toward unity, the separation of the neutron and gamma increases, but the time resolution is poorer. The object is to choose a photoelectron level that will minimize the overlap of rise time of the neutron and gamma-ray signals. Kuchnir and Lynch[1] by using the measured distributions and a more general-order equation predicted the optimum separation to exist when the fraction of pulse height used is between 0.8 and 0.9. The 552 was designed to take advantage of the following experimental conditions.

Consider a typical example where Eqs. (2) and (3) can be used to predict the separation of neutrons and gamma rays. Assume the following experimental conditions:

1. The neutron pulse height is equal to the gamma-ray pulse-height equivalent of 100 keV electron energy or 500 keV neutrons.

2. The scintillator is NE-213 on an RCA-8575 photomultiplier producing 1.7 photoelectrons/keV of electron energy.

3. The effective decay of NE-213 is 130 nsec for neutrons and 10 nsec for gamma rays.

The variance for the neutron rise time is calculated by

$$\sigma_n^2 = \sigma_{10\%}^2 + \sigma_{90\%}^2 \cong \sigma_{90\%}^2$$

$$\sigma_n^2 = (56 \times 10^{-12})^2 \sum_{k=0}^{j} \left(\frac{1}{R-k}\right)^2 \qquad (4)$$

In Eq. (4) R is 1.7 x 100 keV or 170; j = 0.9 x 170, or 152.

Substituting the values of R and k in Eq. (4) yields

$$\sigma_n^2 = (56 \times 10^{-9})^2 \times \left[\left(\frac{1}{170}\right)^2 + \left(\frac{1}{169}\right)^2 + \left(\frac{1}{168}\right)^2 + \cdots \left(\frac{1}{18}\right)^2\right]$$

$$\sigma_n \approx 56 \times 10^{-9} \times 0.22 = 12.2 \text{ nsec},$$

$$\Delta t = 2.35 \times 12.2 = 29 \text{ nsec (FWHM)},$$

*Nuclear Enterprises, Ltd, San Carlos, California.
** See "References" at the end of this paper.

For the gamma ray

$$\sigma^2_\gamma = (4.5 \times 10^{-9})^2 \sum_{k=0}^{j} \left(\frac{1}{R-k}\right)^2$$

$$\sigma_\gamma \approx 4.5 \times 10^{-9} \times 0.22 = 0.95 \text{ nsec},$$

$$\Delta t = 0.95 \times 2.35 = 2.25 \text{ nsec (FWHM)}.$$

The mean separation would be

$$\bar{t}_n - \bar{t}_\gamma = 120 \text{ nsec}.$$

The calculated results are shown in Fig. 1a, with the shapes assumed to be approximately Gaussian. Figure 1b illustrates what happens to the ability to separate the neutrons and gamma rays at approximately 350 keV neutron energy or 70 keV equivalent electron energy. The assumptions used to obtain Eqs. (1) and (2) are representative of first-order approximations and are presented here to illustrate the effect of various parameters on the neutron-gamma separation.

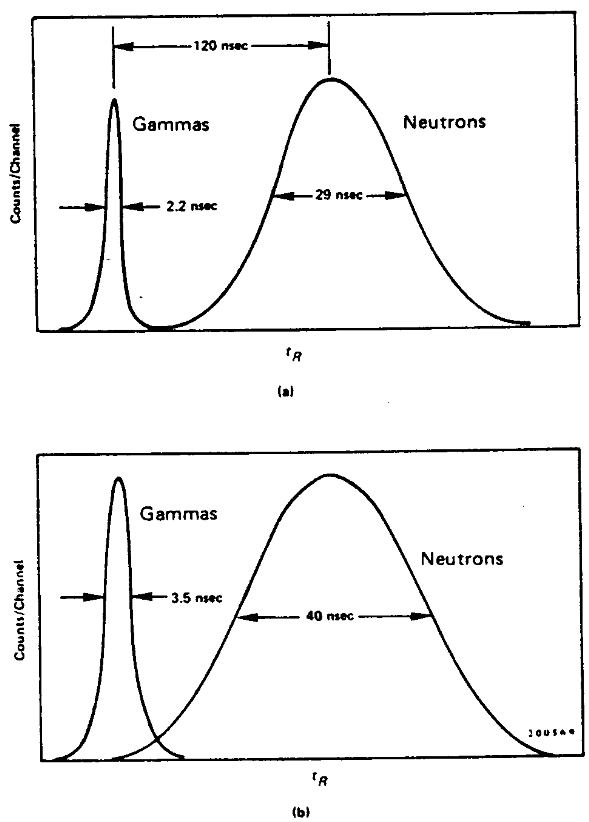

Fig. 1. Calculated Response for (a) 100 keV and (b) 70 keV Electron Equivalent Energies Deposited in NE-213.

Proper Application of the 552 The 552 Pulse Shape Analyzer measures the 90—10% fall time of the linear signal presented to its input. To obtain the best time resolution a fast unipolar delay-line-shaped main amplifier should be used. The rise time of the unipolar delay-line-shaped pulse should not be greater than 100 nsec for best results, and the amplifier should have low noise characteristics and be operated at low gain. Figure 2 shows the process by which a delay-line-shaped pulse is produced. Notice that the time information is inverted in the process of producing the trailing edge of the pulse. The time information that occurs at the 10% point on the input signal occurs at the 90% level on the trailing edge, and the time information occurring at the 90% level on the input signal is transformed to the 10% level on the trailing edge.

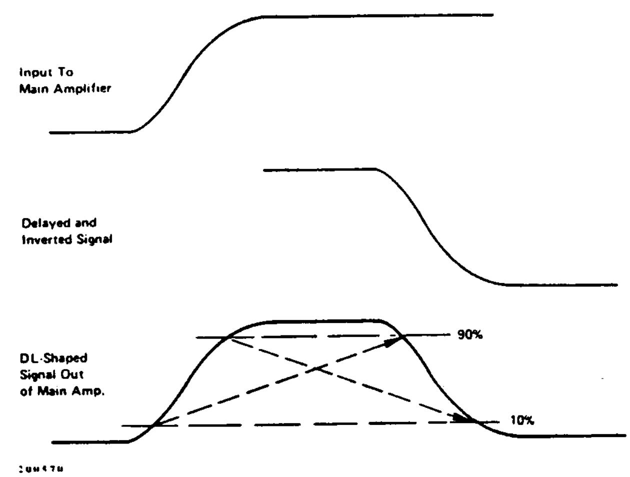

Fig. 2. Single Delay Line Shaped Signal.

Consider the effect of amplifier noise on the neutron-gamma separation for a wide dynamic range of operation. Assume the following amplifier noise characteristics:

Gain = 10
Rise time = 100 nsec
Input equivalent noise (Δv) = 70×10^{-6} V

The rise-time noise is given approximately by

$$\Delta t = \sqrt{2}\; G \; 2.35 \, \Delta v/(v/t_R), \quad (5)$$

where Δv is rms noise at the input, v is the signal level of interest, and t_R is the rise time. The $\sqrt{2}$ factor exists because of two-level measurements and the 2.35 converts the rms value to FWHM. For the example above the time resolution at the minimum pulse height of 20 mV is

$$\Delta t = \sqrt{2}\,(10)\,(2.35)\; 70 \times 10^{-6}/(20 \times 10^{-3}/100 \times 10^{-9})$$

$$= 11.5 \text{ nsec (FWHM)}.$$

Many delay-line amplifiers have good noise characteristics for high gain, but the noise increases very rapidly as the gain is lowered. From the above example it becomes evident that the amplifier must be operated at minimum gain and must have good noise characteristic before neutrons and gammas can be separated over the entire range of 20 mV to 10 V. The ORTEC 460 is the only known delay-line-shaped amplifier with these characteristics.

A typical block diagram for a neutron—gamma-ray discrimination system is shown in Fig. 3. Figure 4 is a typical spectrum of the TAC output with a plutonium-beryllium source. The SCA in the TAC can be set to count only the events in the neutron peak.

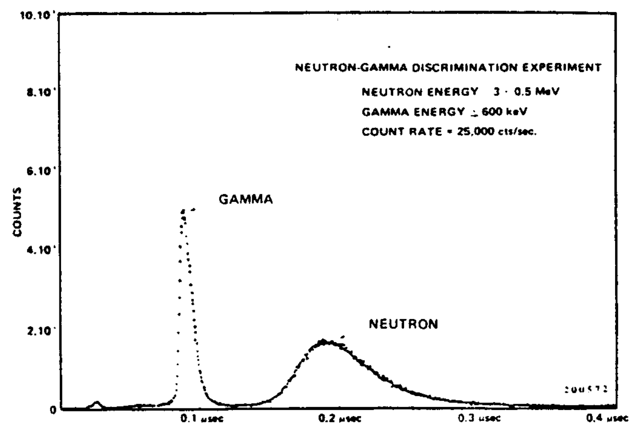

Fig. 4. Neutron-Gamma Rise Time Spectrum.

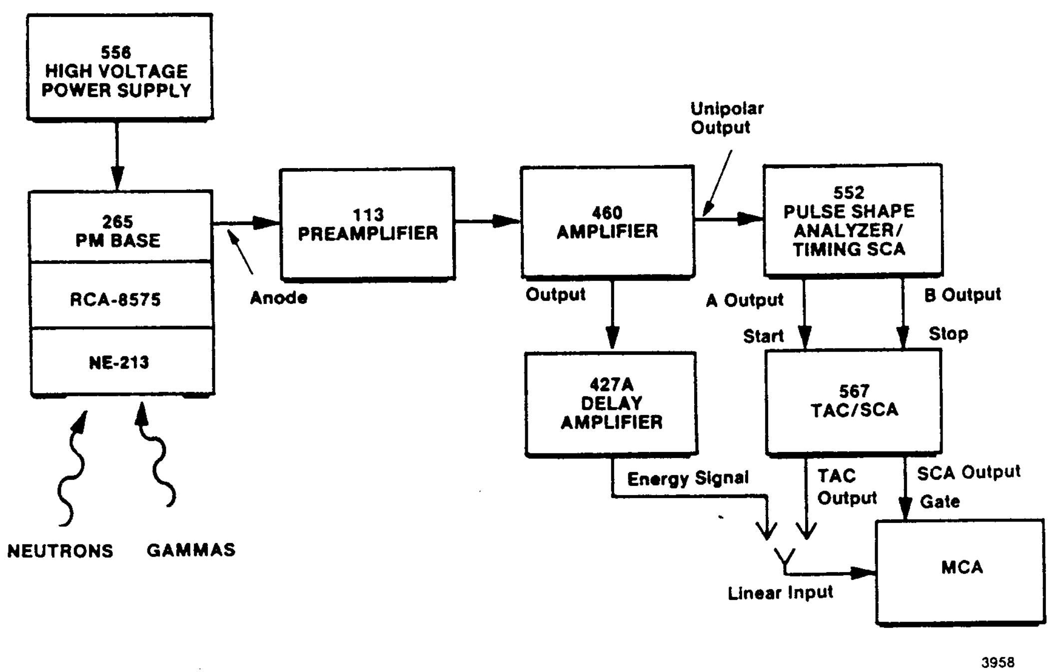

Fig. 3. Block Diagram for a Typical Neutron-Gamma Separation Experiment.

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