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ABSTRACT

Present nuclear experimentation requires millimicrosecond coincidence instrumentation. The object of fast circuitry is to obtain statistically valid results, implying short resolving times with high counting rates. The limitations in obtaining these results lie not only in the electronic circuit, but also in all the associated system components, including the scintillation crystal and photomultiplier tube. A coincidence system is described herein with a discussion of its inherent limitations and methods of improving similar systems.

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1. Introduction

The establishing of causality between nuclear radiations as well as the determination of the decay time of short-lived isotopes has necessitated the detecting of events occurring within millimicroseconds of each other.

Resolving time[1] has generally been the term employed to indicate the figure of merit of a coincidence system; values on the order of 5×10^{-9} to 10^{-10} sec have been reported in literature.[2] Seldom is reference made to the efficiency of a system - i.e., the percent of true coincidences recorded.[3] It appears that a more valid figure of merit of a coincidence system would be coincidence counting efficiency divided by resolving time, denoted in this paper as CFM (coincidence figure of merit).

The coincidence system includes not only the electronic circuit, but also photomultiplier, scintillation crystal, intervening amplifiers, and coaxial cables. All these items have a definite effect upon the system CFM, and are considered separately.

2. Electronic Circuit

At present there are two modified "and" circuits that function well for fast-coincidence experimentation: the circuits by (1) Bell, Graham, and Petch,[4] and (2) Garwin.[5] In both circuits the resolving time is determined by the rise time of the plate voltage, which is linearly related to the $Gm/C_{gk} + C_{pk}$ of the tubes and inversely related to the plate load resistance. The major difference between the circuits is in the ratio of coincidence output to

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[1] Resolving time has been defined in various manners. See UCRL Counting Handbook for definition used in this paper.

[2] Bay, Millimicrosecond Coincidence Circuits, Nucleonics 14, No. 4, 56-60 (1956).

[3] A notable exception, where efficiency is considered, is Bell, Graham, and Petch, Can J. Phys. 30, 35 (1952).

[4] Bell, Graham, and Petch, Can. J. Phys. 30, 36 (1952).

[5] R.L. Garwin, Rev. Sci. Instr. 21, 569 (1950).

a single output--Bell's circuit ratio is 2:1; Garwin's circuit ratio in the 2×10^{-9}-sec region is better than 5:1. Bell inserts a biased diode clipper after the coincidence circuit to prevent feed-through of singles. It is possible, however, that drift might change the clipping level, allowing false outputs. Therefore, the Garwin circuit with a higher singles-rejection ratio was used in the system described herein. The complete schematic with the Garwin coincidence circuit, pulse stretcher, two-stage amplifier, and one-shot multivibrator is shown in Fig. 1.

The operation of the circuit is as follows: Negative pulses of 2 v amplitude and width down to 2.5 mμsec may be used in this circuit with 100% counting efficiency. A single input pulse gives an output at the plate of V1 and V2 of 0.1 v amplitude. A coincident input produces a 0.6-v output pulse; the width is determined by the overlap of the input pulses. The coincident output pulse is then passed through a diode stretcher D3 in order to provide a time base sufficient to trigger the one-shot multivibrator, V5 and V6. Between the stretcher and the one-shot is a two-stage shunt-compensated amplifier, corrected for undershoot, with an over-all gain of 20. The output pulse from V4, a 15-v positive signal, about 0.4 μsec wide, triggers the one-shot, whose firing level is set by a cathode bias potentiometer. The coincidence unit output pulse, taken from the plate of V6, is 1 μsec, 25 v, of positive polarity, with a 0.05-μsec rise time which may be used to gate a scaler or a slow postcoincidence circuit. The desired resolving time of the coincidence unit is obtained by delay-line clipping of the input pulses. The resolving time may be decreased below 2.5 mμsec by shorter clipping lines; but this is unnecessary since the limitation on a high CFM is not due to the electronic circuit, but rather to the detector.

3. The Detector

A photomultiplier with a scintillation crystal as a detector imposes stringent limitations on the resolving time of the system. There are three statistically varying delays which cannot be compensated for by inserting delay lines in either leg of the circuit. They are:

a. Delay in the emission of the first photoelectron from the photocathode.

b. Variations in transit time from cathode-to-dynode No. 1.

c. Varying transit-time spread in the photomultiplier.

Phosphor delay has been investigated by Post and Schiff[6] and confirmed by Bell.[7] The mean time delay for the appearance of the first photoelectron after the passage of a nuclear particle is given by

$$t = \frac{T}{R} \left(1 + \frac{1}{R}\right),$$

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[6] R. F. Post and L. Schiff, Can. J. Phys. 80, 1113 (1950).

[7] Bell et al., Phys. Rev. 30, 36 (1950).

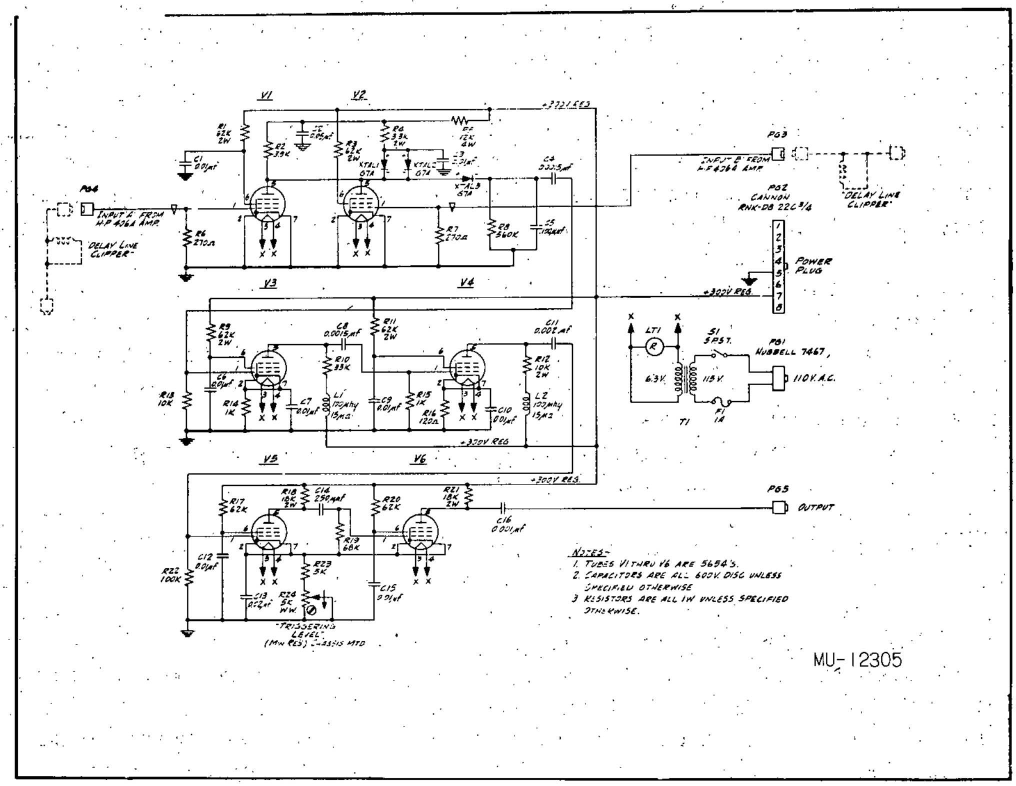

Fig. 1. Millimicrosecond coincidence unit schematic

where T = mean life of the light flash from the phosphor and R = total number of photoelectrons emitted from photocathode as a result of one entering particle. Bell has shown that the minimum resolving time with 90% coincidence efficiency for a 100-kev radiation is 1×10^{-9} sec with stilbene and 4×10^{-9} sec with anthracene. Present calculations for NaI (Tl) with $T = 0.25 \times 10^{-6}$ sec and $R = 1000$ electrons per Mev indicate a minimum resolving time of 15 mμsec. It is convenient to denote this phosphor limitation as T_p. The demands of pulse-height resolution in the present system made the use of NaI (Tl) crystals (with their long T_p) mandatory.

The spread in transit time between the cathode and dynode No. 1 has been investigated recently and has been found to be as much as 7 mμsec in a Dumont No. 6292 photomultiplier.[8] This has been attributed to the nonuniform electrostatic field between dynode No. 1 and the photocathode--the weakening of the field at the edges slows down the passage of electrons. The RCA 5819 photomultiplier with a convex photocathode partially alleviates this difficulty--values of 2.3 to 3.0 mμsec spread have been obtained. In the present application the 6292 tube has been found most satisfactory for pulse-height resolution; and, consequently, the 7-mμsec cathode transit-time spread must be accepted as a further limitation on the resolving time of the system. The cathode-to-dynode No. 1 delay is denoted here as T_c.

The third statistical delay is that produced by transit-time spread between dynode No. 1 and the anode. This time spread varies with individual pulses and is about 0.5 mμsec rms between adjacent dynodes in a typical photomultiplier.[9, 10, 11] Investigators differ somewhat on this value; but since it appears rather conservative, it is used here. The total varying spread in transit time for the tube is thus, with the ten stages, $\sqrt{10} \times 0.5 = 1.65$ mμsec, denoted here as T_t.

The over-all minimum resolving times is then $T_r = \sqrt{T_p^2 + T_c^2 + T_t^2} =$ 16.7 mμsec for 90% efficiency. This agrees quite well with the length of clipping line required to obtain maximum counting efficiency in the present system. The effect of shorter clipping lines is to reduce the counting rate; i.e., it is less than 50% of the maximum rate with 6 mμsec clipping. The above calculations are for 100-kev radiations, and the T_p is the major factor in the resolving time. Higher-energy, monoenergetic pulses permit decreasing the resolving time while maintaining the high efficiency. With pulse-height analysis, the energy spectrum ranges from 50 kev upward; therefore, better resolution is not possible.

4. Amplification and Transmission

The pulses used to trigger the coincidence unit are taken directly from the anode of the photomultiplier and fed into 125-ohm RG 63/U cable. This technique reduces the capacitive loading to a minimum, thereby preserving the rise time of the output pulse as it appears at the anode. The RC time is 125 ohms (cable surge impedance) x 3.3×10^{-12} μf (anode-to-ground capacitance). The coaxial cable is terminated in 330 ohms at the

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[8] R. V. Smith, Nucleonics (April 1956) Vol. 14 No. 4 p. 55

[9] G. A. Morton, Nucleonics 10, No. 3, 39 (1952).

[10] Robt. K. Swank, Nucleonics 12, No. 3, 19 (1954).

[11] I. A. D. Lewis and F. H. Wells, Millimicrosecond Pulse Techniques, McGraw-Hill New York, 1954 p. 257.

input at a H-P 460A distributed amplifier (input impedance 200 ohms). Four H-P 460A amplifiers in cascade are required to amplify 40-kev pulses to 2 v in order to trigger the coincidence unit. All larger pulses are cutoff-limited by the amplifiers. The four amplifiers have a gain of 10^4 and an over-all rise of 5.2 mμsec. In systems where the resolving time T_r of the phosphor and the photomultiplier are in this region, the H-P amplifiers would be the limiting factor.

The dynode No. 10 provides the pulses for the preamplifier and subsequent pulse-height analysis. Figure 2 is a block diagram of the fast-coincidence system, showing its relation to the over-all instrumentation.

5. Noise

The limitation on low-energy coincidence counting is the noise level of the H-P amplifier, which is between 50 and 100 microvolts at the input. Proper choice of amplifiers and tubes with low noise figures has permitted the counting down to 40-kev radiations without false coincidences. Higher-current photomultipliers would permit the elimination of at least one H-P amplifier, increasing the signal-to-noise ratio by 10.

6. Conclusion

Several areas for the improvement of the CFM have presented themselves in the course of this project. In experiments that do not require pulse-height analysis, stilbene, anthracene, or plastic phosphors would bring the resolving time with high counting efficiency into the 5 mμsec region. Photomultipliers with more uniform cathode-dynode No. 1 electrostatic fields would decrease T_c. Higher-impedance coaxial cables connected at the anode would increase the signal-to-noise ratio, i.e., use of Transradio C3T, 200 cable in the present system would improve this ratio by a factor of nearly two. Higher-current tubes, such as the Dumont 6810, might provide sufficient signal across a 200-ohm termination to permit the elimination of all the H-P amplifiers and their attendant rise time. And finally, smaller crystals of about 0.6 in. diameter would reduce the cathode-to-dynode No. 1 transit time spread--an application limited to cases in which smaller resolving time is more important than detection efficiency.

The above discussion was for the most part limited to the present system, which was engineered for Dr. Frank Asaro of UCRL. An excellent, rigorous analysis on the problem of scintillation counter statistics has been made by Ernst Breitenberger.[12] It is hoped that this discussion has sufficiently emphasized the need for caution when defining resolving time in millimicrosecond coincidence instrumentation.

This work was done under the auspices of the U.S. Atomic Energy Commission.

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[12] Ernst Breitenberger, Scintillation Spectrometer Statistics, in Progress in Nuclear Physics, O. R. Frisch, Ed., Vol. 4 Pergamon Press, 1955, p. 56.

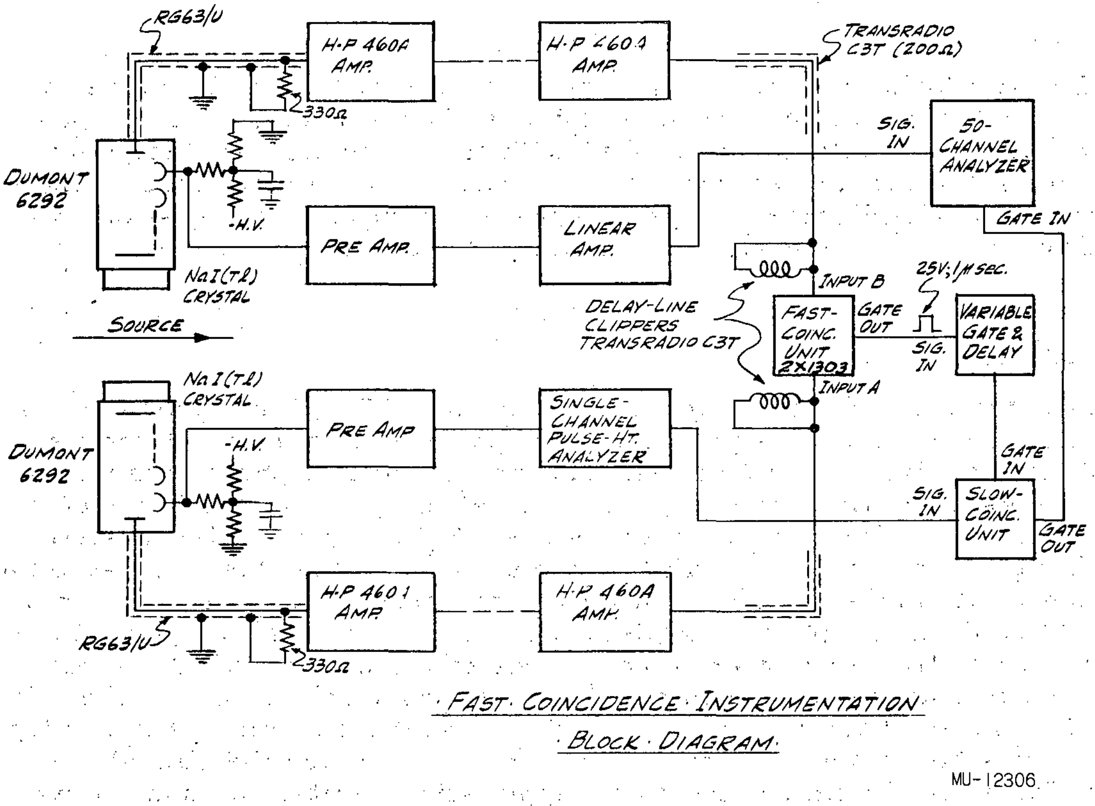

Fig. 2. Fast coincidence instrumentation block diagram.

Radiation Laboratory
University of California
Berkeley, California

December 3, 1956

To: Instrumentation Distribution

From: Technical Information Division

Re: UCRL-3539 - Errata

Please make the following corrections in your copies of UCRL-3539:

On page 4 Reference 7 should read

[7] Bell et al., Can. J. Phys. 30, 36 (1950).

On page 6 Line 5 of Section 4 should read

. . . . . 3.3 x 10^{-12} f (anode-to-

On page 7 Line 9 of Section 6 should read

. . . . . such as the RCA 6810, might