Time Resolution of a Transistorized Time-of-Flight System

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Received June 21, 1965

Construction and performance of a transistorized time-of-flight system are described. Timing signals are obtained from a discriminator in which a fast tunnel diode is used, and the time intervals between two signals are converted to pulse heights by a time-to-pulse height converter of Culligan and Lipman type.

The time resolution obtained with pulses from a standard mercury pulser is less than 10^{-10} sec in full width at half maximum. The full width at half maximum of a Co^{60} γ-γ coincidence curve was 1.48×10^{-9} sec, using RCA-6810A and RCA-6655A photomultipliers coupled with thick plastic scintillators which are 65 mm in diameter, 60 mm thick and 50 mm in diameter, 60 mm thick, respectively. The comparison with theoretical estimations of the time resolution has been made, and several causes of the finite time resolution are discussed.

1. INTRODUCTION

The increasing interests in the studies of elastic and inelastic neutron scatterings and the need for more accurate measurement of life time of excited states of nuclei have stimulated the outgrowth and the refinement of the techniques of the time interval measurement in the nanosecond and subnanosecond range. Availability of fast switching transistors and the development of fast photomultipliers with suitable scintillators have greatly improved the accuracy of time measurement. Among several methods of time measurement[1], time-to-pulse height conversion is now most conventional. Some types of transistorized time-to-pulse height converters have been presented[2,3,4].

With the improvement of the techniques, the limitation of the time measurement system has been frequently discussed, and the several theories have been presented[5~12]. Unfortunately these theories are not completely consistent with each other and several adjustable parameters involved seem to have large uncertainty. Some experimental studies on the time resolution of scintillation counter and photomultiplier system have been performed[13~16]. In some cases, the results are not in agreement with the theoretical predictions. Thus it is thought useful to accumulate the experimental data for further studies.

A time-to-pulse height converter of Culligan and Lipman type[2] was constructed in our laboratory and the time resolution of our time-of-flight system was measured. Some causes of the finite time resolution are discussed.

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2. ELECTRONIC CIRCUITRY AND COUNTERS

A block diagram of the time-of-flight system is shown in Fig. 1. Figs. 2 to 6 give the circuit diagrams of each element of the block diagram. In order to match the current level and the timing between elements, 75Ω attenuators and delay lines are used when neccessary.

The time-to-pulse height converter shown in Fig. 2 requires input pulse height between 3 and 10 volts. Therefore 7 mA output current pulses from discriminators are amplified by fast amplifiers which have a few nsec risetime and the gain of about 25 db and then stepped up by ferrite core transformers.

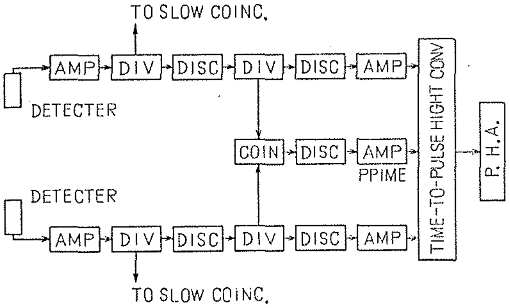

Fig. 1. Block diagram of the time-of-flight system.

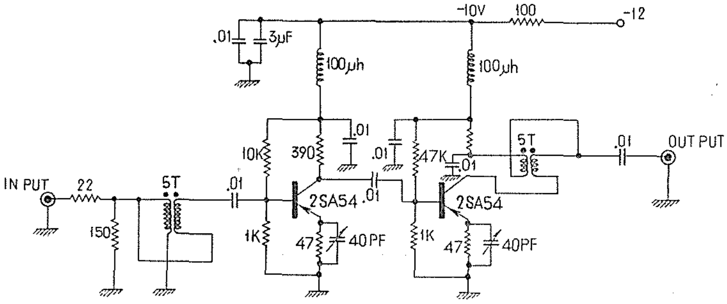

Fig. 2. Circuit diagram of the fast amplifier.

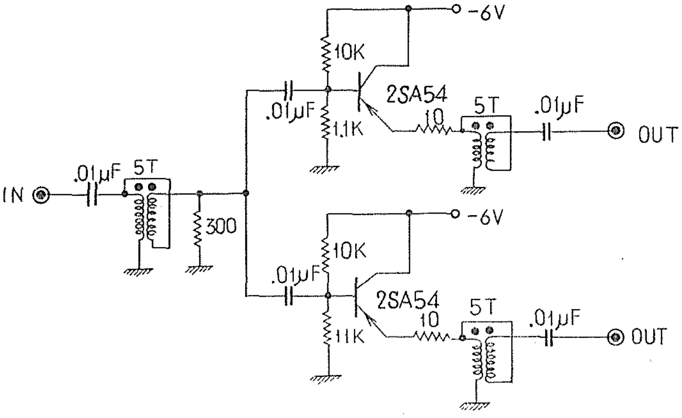

Fig. 3. Circuit diagram of the divider.

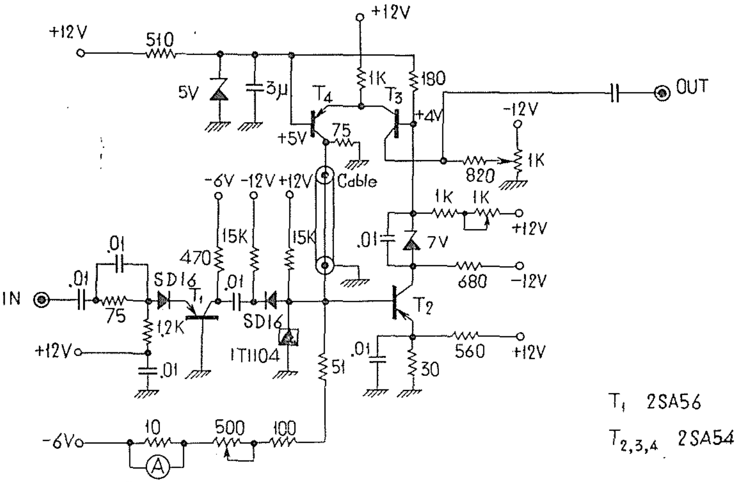

Fig. 4. Circuit diagram of the discriminator.

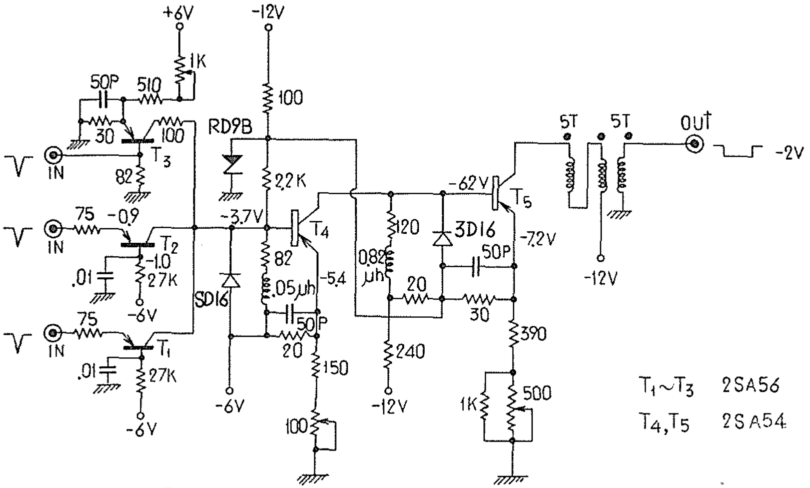

Fig. 5. Circuit diagram of the fast coincidence.

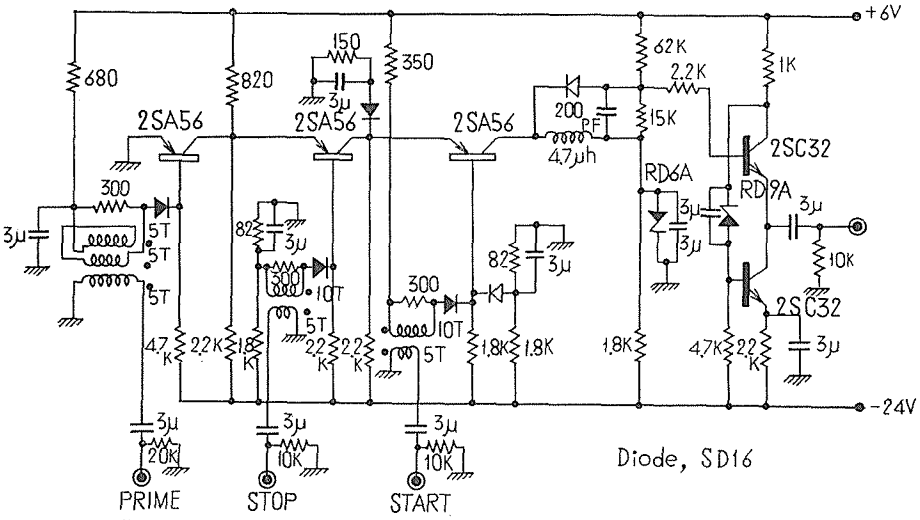

Fig. 6. Circuit diagram of the time-to-pulse height converter.

The ferrite core transformer is also used as phase inverter for the "stop" pulse. The time converter needs "prime" pulse which gates the time converter only when a "start" pulse and a "stop" pulse have occurred within the required time range. This "prime" pulse is fed from a coincidence circuit of which resolving time is determined by both output pulses of the fast tunneldiode discriminators*. The resolving time of the coincidence circuit defines the time range to be measured. The discriminators are also used for shaping the pulses fed to the time converter. The pulse width of the discriminator output can be changed by varying the length of coaxial cable.

The widths of three input pulses fed into the time converter should be carefully selected. The leading edge of the "prime" pulse should precede the leading edge of the "start" pulse by more than 30 nsec. Otherwise, the output pulse height depends on the time interval between the leading edges of the "prime" and the "start" pulses. Therefore the width of the "prime" pulse shoud be 30 nsec longer than the time interval to be measured. The width of the "stop" pulse should be longer than the width of the "start" pulse plus the time interval to be measured so that the output of the time converter may not be produced when the "stop" pulse precede the "start" pulse. Output pulses of the time converter are fed to a TMC 400 channel pulse height analyzer.

The counter for "start" pulses is of a 50 mm in diameter, 60 mm thick plastic scintillator mounted on an RCA-6655A photomultiplier. The counter for "stop" pulses is of a 65 mm in diameter, 60 mm thick plastic scintillator mounted on an RCA-6810A photomultiplier. The divider circuits of the photomultipliers

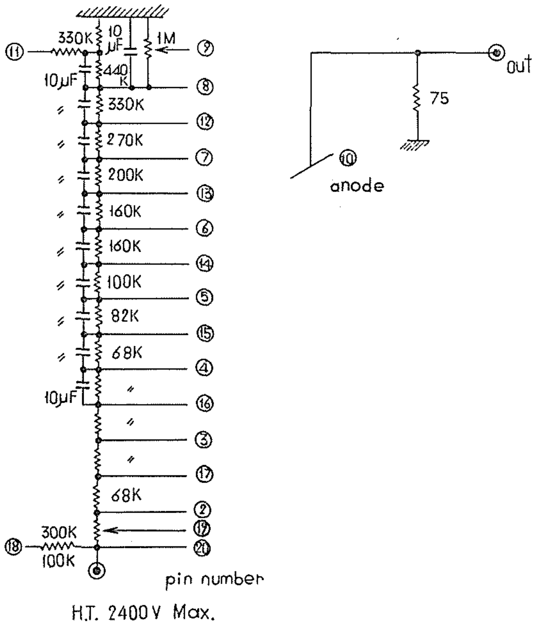

Fig. 7. Divider circuit for a 6810A photomultiplier.

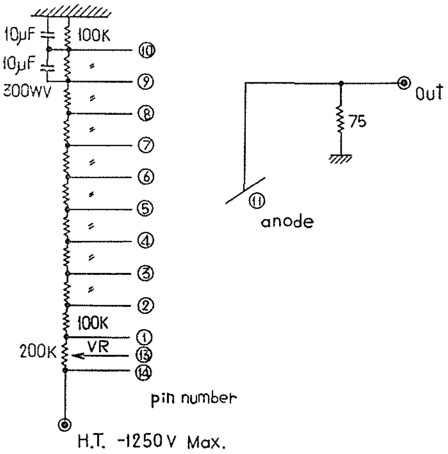

Fig. 8. Divider circuit for a 6655A photomultiplier.

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* The discriminator shown in *Fig. 4 is a revised one originally presented by* Sugarman[5].

are shown in Figs. 7 and 8.

3. PERFORMANCE

A linearity curve of the time-of-flight system in the time range of 10 nsec is shown in Fig. 9. This curve was obtained with single photomultiplier pulses from Co^{60} γ-ray source and with a variable delay line.

Time resolution of the time-of-flight system have been measured in the following three ways. First, pulses of less than 1 nsec rise time from a mercury

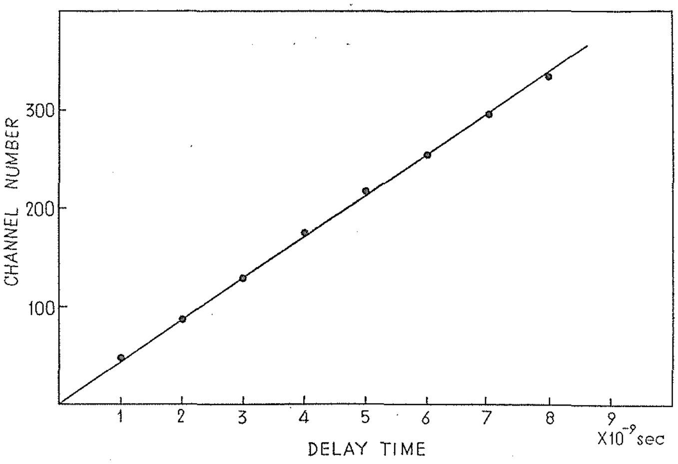

Fig. 9. Linearity curve of the time-of-flight system in the time range of 10 nsec.

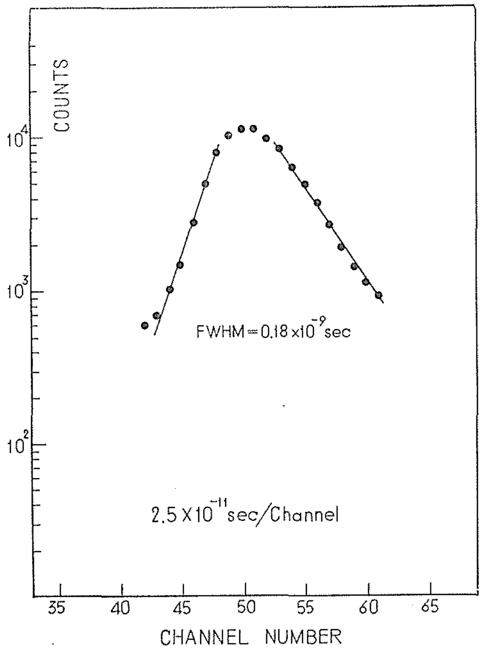

Fig. 10. Resolution curve obtained with pulses from the single photomultiplier caused by Co^{60} γ-rays.

double pulser were fed to two fast amplifiers. The measured resolution was less than 2.5×10^{-11} sec in full width at half maximum. Secondly, pulses from a single photomultiplier caused by Co^{60} γ-rays were used to measure the time resolution. In this case, the resolution was less than 1.8×10^{-10} sec in full width at half maximum as shown in Fig. 10. It may be considered that this finite time resolution is mainly attributed to the fact that the triggering time of the discriminator varies with the input pulse height. Lastly, Co^{60} γ-γ coincidence spectrum was measured to test the overall time resolution of the system. An about 0.3 milli-Curie source of Co^{60} was viewed with the two plastic scintillators and collimators. Collimators were of 20 cm long with a rectangular aperture of 1.5 cm×2.0 cm placed at an angle of about 175 degrees to each other in order to obtain clearer Compton edge and to prevent the backscattered γ-rays from each scintillator in the pulse height spectrum. Usual slow concidence technique was employed to select the pulse height. Output pulses of the slow coincidence circuit are used to gate a TMC 400 channel pulse height analyzer. A typical Co^{60} prompt curve without pulse height selection in the side channels is shown in Fig. 11. The full width at half maximum of the curve was 3.7×10^{-9} sec. The prompt curve shown in Fig. 12 was obtained by selecting the pulse height from both counters corresponding to the Compton edges with an accuracy of about 20%. The full width at half maximum was 1.48×10^{-9} sec. Further improvement of the time resolution was not obtained with the narrower channel width

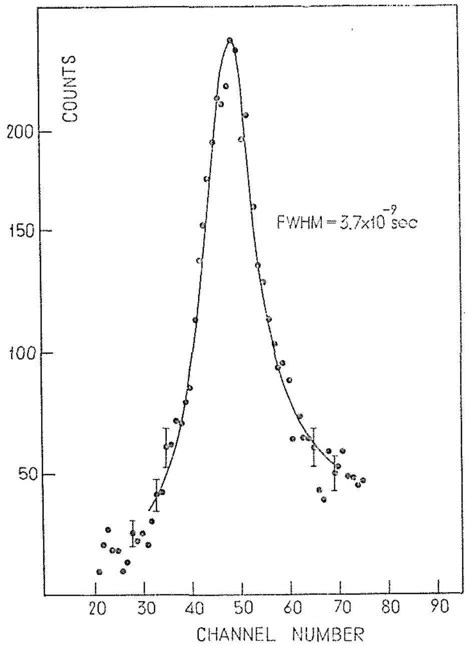

Fig. 11. Promt Co^{60} γ-γ coincidence curve without pulse height selection in the side channels.

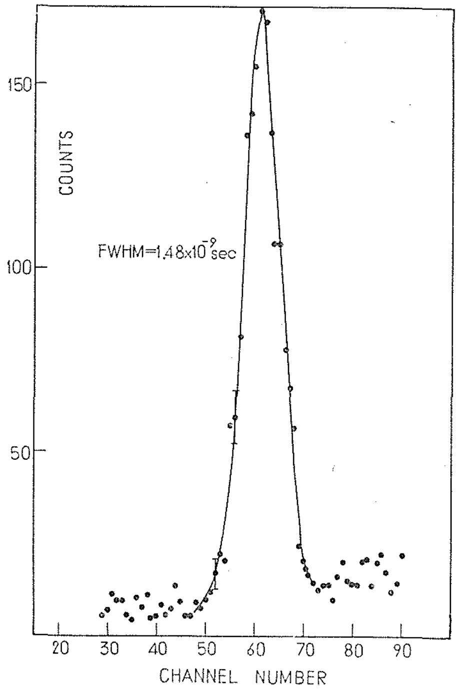

Fig. 12. Prompt Co^{60} γ-γ coincidence curve obtained by selecting the pulse height in the side channels with an accuracy of about 20%.

selecting the pulse height.

Time drift of less than 10^{-10} sec was observed over a period of 10 hours when a mercury double pulser was used. The time drift may be caused, for example, by drift of transistor supply voltages, change of characteristics of transistors with temperature and instability of the multichannel analyzer. The definite causes of time drift could not be quantitatively revealed.

4. DISCUSSION

The finite time spread of prompt cascade spectrum comes from various sources. It sould be noticed that the detection process of particles in the scintillation counter consists of the following[18,19] :

1. Interaction of an incident particle with the scintillator, leading to excitation of optically active states.
2. Decay of the excited states and consequent emission of light.
3. Collection of the emitted light and emission of photoelectrons from the cathode of phototube.
4. Formation of the electron cascade.
5. Processing of the output current by suitable electronic instrumentation.

Several experimental and theoretical studies[5~16] have been done to know the time spread caused by these processes. Most important sources of finite time spread are mainly due to the statistical properties of pulses from the detectors, that is, scintillator decay time and photomultiplier time jitter. The analysis of the time spread by Post and Schiff[5] in 1950 was concerned only with the decay time of the scintillator. Their analysis gives minimum time spread when a very small fraction of the total current pulse from the photomultiplier is used to obtain the timing signal, and that is obtained by, for example, triggering the discriminator at very low level compared with the pulse height. The statistical properties of detector signals can be fully described by[6] :

1. The statistical properties of the photoelectronic emission from the photocathode lit by a given flash from a particular scintillator. This is represented by an "Illumination" function after Gatti and Svelto[6].
2. The single electron response of the electron multiplier.

The "Illumination" function is characterized by the decay time of the scintillator and the single electron response is characterized by three statistical variables λ, A, h and their variances $\epsilon^2{}_{\lambda}$, $\epsilon^2{}_{A}$, $\epsilon^2{}_{ph}$, where λ is the mean square width of current pulse, A is the average gain and h is the average time position with respect to the time of emission of the photoelectron.

The time spread was calculated as a function of these variables by Gatti and Svelto[6]. They found the minimum of time variance at a certain value of C/R, where C, a fraction of the total current pulse R, is the definite charge by which the timing signal is produced. Several experimental values of time resolution have been reported to be in agreement with their calculated values, although the quantitative agreement is not so good in some cases[13,14,20]. Schwarzschild[13] measured the time spread for a rather large range of C/R, and obtained the minimum of time variance at $C/R \simeq 0.2$. The same experimental results have been obtained by Barl and Weinzierl[14]. And in our case, the measured time resolution is nearly in agreement with that predicted by the theory of Gatti and Svelto.

However, the method of the so called "machine time" determination by Schwarzschild which is the same method as ours seems not to coincide strictly with that presented by Gatti and Svelto. In the case of Schwarzschild as well as ours, the machine time is defined with the time at which a tunnel diode of the discriminator is triggered at a certain current level, while Gatti and Svelto define the machine time as the time at which a definite fraction of the integrated current pulse is collected at the output of the photomultiplier.

Recently, Gatti and Svelto re-examined their calculation which lead to a minimum of the time variance as a function of C/R and found their previous calculation was wrong[21]. They ascribed their errors to the evaluation of the contribution to the variance from the transit time fluctuations. As the corrected results have not yet been reported, we can not compare our experimental results with the corrected calculation.

On the other hand, Hyman[10] calculated recently the time variance of photomultiplier system. The calculation is a generalization of the previous work of Hyman and Schwarz[9] that have been done only for 56 AVP photomultipliers. A clipped Gaussian was assumed for a single electron response function and the time variance was calculated by a Monte Carlo method and also by an analytical method. The results are shown in graphical form in Ref. (10).

For the comparison of Hyman's results with experiment, it is necessary to specify the quantities $\sigma\mu$, σ'/σ and γ presented in Ref. (10). Considering the shape of the anode current of the photomultiplier, one can assume that γ is infinitely large. The decay time, $1/\mu$, of the scintillator* is assumed to be about 3×10^{-9} sec, σ, the standard deviation of the clipped Gaussian, is assumed to be 3.0×10^{-9} sec for the 6655A photomultiplier and 0.7×10^{-9} sec for the 6810A photomultiplier. For both counters, C and R are estimated as follows:

6655A: $R=200$, $C/R=0.2$.
6810A: $R=100$, $C/R=0.2$.

The time resolution in the case of the parameters $\sigma\mu=1$ (6655A) and $\sigma\mu=1/4$ (6810A) are, if assumed $\sigma'/\sigma=1$, estimated to be 0.85×10^{-9} sec and 0.64×10^{-9} sec, respectively, from Fig. 3 in Ref. (10). Then the time resolution in our time-of-flight system is estimated as

$$\sqrt{(0.85 \times 10^{-9})^2 + (0.64 \times 10^{-9})^2} = 1.06 \times 10^{-9} \text{ sec.}$$

This value is rather small compared with the value of 1.48×10^{-9} sec obtained in the present experiment. Considering the parameter σ for 6810A may be larger than the above-estimated value of 0.7×10^{-9} sec, the agreement between the theory and the experiment should become good.

Further improvement of the time resolution of time-of-flight system may be

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achieved by selecting the detection and amplification method of information signals of shorter decay time and of narrower transit time spread, respectively, for example, by use of a Čerenkov counter, and of limited area of photomultiplier cathode.

ACKNOWLEDGEMENTS

The authors wish to thank Profs. K. Kimura, Y. Uemura, T. Yanabu and J. Muto and Dr. I. Kumabe for their interests and encouragement throughout this work. They also thank the members of the cyclotron laboratory and the high energy physics group of Kyoto University for assistance and advice on preparation of the apparatus.

REFERENCES

(1) J. B. Neiler and W. M. Good, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler, (Interscience Publishers, Inc., New York, 1960), Part 1, Chapter IV A.
(2) G. Culligan and N. H. Lipman, *Rev. Sci. Instr*, 31, 1209 (1960).
(3) D. Ophir, *Nucl. Instr. and Meth.*, 28, 237 (1964).
(4) D. Bloess and F. Münnich, *Nucl. Instr. and Meth.*, 28, 286 (1964).
(5) R. Post and L. I. Schiff, *Phys. Rev.*, 80, 1113 (1950).
(6) E. Gatti and V. Svelto, *Nucl. Instr. and Meth.*, 4, 189 (1959).
(7) S. Collombo, E. Gatti and M. Pignanelli, *Nuovo Cimento*, 5, 588 (1959).
(8) M. El-Wahab and J. V. Kane, *Nucl. Instr. and Meth.*, 15, 15 (1962).
(9) L. Hyman and M. Schwarz, *Rev. Sci. Instr.*, 35, 393 (1964).
(10) L. Hyman, *Rev. Sci. Instr.*, 36, 193 (1965).
(11) L. Beghian, G. Kegel and R. Schranberg, *Rev. Sci. Instr.*, 29, 753 (1958).
(12) H. Jungclaussen, *Nucl. Instr. and Meth.*, 27, 88 (1964).
(13) A. Schwarzschid, *Nucl. Instr. and Meth.*, 21, 1 (1963).
(14) W. Barl and P. Weinzierl, *Rev. Sci. Instr.*, 27, 226 (1957).
(15) F. T. Arecchi, A. De Matteis and E. Gatti, *Energia Nucleare*, 7, 697 (1960).
(16) W. M. Curie, R. F. Azuma and G. M. Lewis, *Nucl. Instr. and Meth.*, 13, 215 (1961).
(17) R. Sugarman, F. C. Merritt and W. A. Higinbotham, *Nanosecond Counter Circuit Manual*, BNL 711 (T-248) (1962).
(18) Curran, "*Luminescence and the Scintillation Counter*", (Butterworths Scientific Publications., (London, 1953).
(19) J. B. Birks, "*Scintillation Counters*", (Pergamon Press Ltd., London, 1953).
(20) R. E. Bell, S. Bjornholm and J. C. Serviens, *Mat. Fys. Medd. Dan. Vid. Selesk.*, 32, No. 12 (1960).
(21) E. Gatti and V. Svelto, *Nucl. Instr. and Meth.*, 30, 213 (1964).