



The use of scintillation counters for determining absolute radioactive decay rates by coincidence methods  
by Philip Charles Finch

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Engineering Physics  
Montana State University  
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**Abstract:**

A method of determining the absolute decay rate of a radioactive substance is described, wherein use is made of three counting rates. The difficulties resulting from the application of scintillation counters to this problem are discussed, and methods for avoiding some of these problems are presented. Circuit diagrams of a gain-stabilized photomultiplier circuit, an amplifier circuit, and a coincidence circuit are shown. The results obtained by applying the method to two samples of Co60 indicate that reasonable accuracy may be expected, although a definite statement as to the accuracy of the method must await a more complete investigation into the effects of satellite after-pulsing in photomultiplier tubes.

THE USE OF SCINTILLATION COUNTERS FOR DETERMINING  
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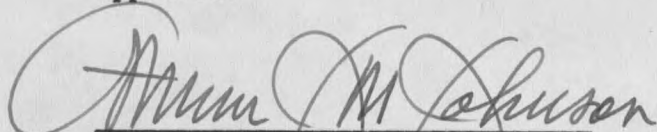
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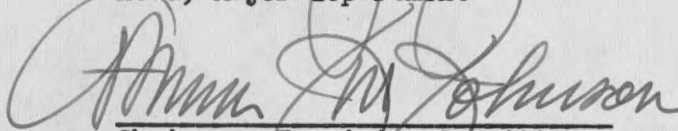
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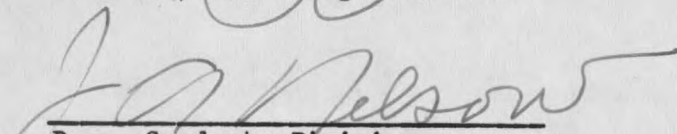
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Bozeman, Montana  
June, 1954

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ABSTRACT

A method of determining the absolute decay rate of a radioactive substance is described, wherein use is made of three counting rates. The difficulties resulting from the application of scintillation counters to this problem are discussed, and methods for avoiding some of these problems are presented. Circuit diagrams of a gain-stabilized photo-multiplier circuit, an amplifier circuit, and a coincidence circuit are shown. The results obtained by applying the method to two samples of  $\text{Co}^{60}$  indicate that reasonable accuracy may be expected, although a definite statement as to the accuracy of the method must await a more complete investigation into the effects of satellite after-pulsing in photo-multiplier tubes.

## INTRODUCTION

Coincidence counting methods have been used extensively since 1930 as a means of studying cosmic radiations, Compton effect, and in the determination of quantum energies. All of these experiments involve the "simultaneous" triggering of two counting devices by a single particle or quantum. "Simultaneous" events are registered by some coincidence device, and any two events that occur within the resolving time of this device are considered as simultaneous events.

In 1939, Feather and Dunworth (5) began coincidence measurements of a somewhat different nature for a new purpose--the detection of the simultaneous emission of two particles or quanta by an atomic nucleus. A portion of the experiments was directed towards the determination of the absolute efficiencies of the Geiger-Müller counters for various gamma radiations, and towards the determination of the absolute intensity of the sources.

Recent advances in the design of photomultiplier tubes have permitted the scintillation counter to replace the Geiger-Müller counter for many counting purposes. The application of scintillation counters to the problem of determining the absolute decay rate of a  $\text{Co}^{60}$  source by the Dunworth method is the subject of this report.

#### DERIVATION OF THE EXPRESSION FOR ABSOLUTE DECAY RATES

Coincidence counting involves registering the detection of two events that occur within a predetermined time interval. Such events are considered to be simultaneous events.<sup>1</sup> In the problem of determining absolute decay rates, the simultaneous events to be detected are the emission of two ionizing particles or quanta by a single nucleus in the process of its radioactive decay. Indicated coincident events may result from one of three different processes. These processes may be described in the following manner:

1. A single particle may pass through both detectors and activate both.
2. The detectors may be activated by separate particles which are the result of a single nuclear decay.
3. The detectors may be activated by particles which have their origins in separate, uncorrelated events that have occurred within the necessary time interval.

Coincidences of the first type are the result of cosmic radiation. The position of the two detectors relative to one another determines to a large extent how significant the error introduced by coincidences of this type may be. By arranging the detectors in a horizontal plane, the

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1. The time interval (the resolving time) within which two events must occur to be considered as coincident or simultaneous events may vary within rather wide limits according to the requirements of any problem. Resolving times on the order of  $10^{-7}$  seconds are easily obtainable, and Z. Bay (2) has shown that resolving times as short as  $3 \times 10^{-10}$  seconds are obtainable with the proper choice of equipment.

probability of such an event is reduced to the extent that such coincidences do not introduce an appreciable error.

Coincidences of the second type are the genuine or true coincidences to be investigated.

Coincidences of the third kind are the result of the finite resolving time of the equipment. The error introduced by these chance coincidences is determined by the resolving time of the coincidence circuits and by the activity of the source. In most cases, it is desirable to keep the number of these coincidences at a minimum.

Consider the case in which a nucleus undergoes a radioactive transformation with the simultaneous emission of two particles. Let  $\epsilon_1^1$  denote the total probability that particle number one will be detected by counter number one, and  $\epsilon_2^1$  the probability that particle number one will be detected by counter number two. Let  $\epsilon_1^{11}$  and  $\epsilon_2^{11}$  represent the corresponding probabilities for particle number two. These probabilities are dependent upon the solid angles subtended at the source by the two detectors, the efficiency of the detectors, the sensitivity of the electronic circuits involved, the efficiency of the optical coupling, etc. With the probabilities defined as above, the following relationships may be written:

$$N_1 = N (\epsilon_1^1 + \epsilon_1^{11}) \quad (1)$$

$$N_2 = N (\epsilon_2^1 + \epsilon_2^{11}) \quad (2)$$

where  $N_1$  represents the counts per second by counter number 1,  $N_2$  the counts per second by counter number 2, and  $N$  the number of decays per second.

True coincidence counts may arise in two different fashions. Particle number one may be detected by counter number one and the associated particle number two by counter number two. The probability of this event would be  $\epsilon_1^1 \epsilon_2^{11}$ . Particle number one may be detected by counter number two and the associated particle by counter number one. The probability of this event is  $\epsilon_1^{11} \epsilon_2^1$ . The probable number of true coincidence counts is given by the expression:

$$N_c \text{ (coincidence counts)} = (\epsilon_1^1 \epsilon_2^{11} + \epsilon_1^{11} \epsilon_2^1) N \quad (3)$$

If the relative efficiencies of the counters towards the two particles are known, such that:

$$\epsilon_1^{11} = K \epsilon_1^1 \quad (4)$$

$$\epsilon_2^{11} = K \epsilon_2^1 \quad (5)$$

Then: 
$$N_1 = N \epsilon_1^1 (1 + K) \quad N_2 = N \epsilon_2^1 (1 + K) \quad N_c = 2NK \epsilon_1^1 \epsilon_2^1 \quad (6)$$

The decay scheme of  $\text{Co}^{60}$  involves the emission of a  $\beta$ -particle followed by the emission of two gamma rays with energies of 1.17 Mev. and 1.33 Mev. By screening out the  $\beta$ -particles by means of aluminum shields, the problem of determining the activity of a  $\text{Co}^{60}$  source is reduced to the problem discussed above. Furthermore, since the two gamma rays are of very nearly the same energy, it may be stated with little error that  $K$ , the relative efficiency, is equal to unity. The equations then

become: 
$$N_1 = 2N \epsilon_1^1 \quad N_2 = 2N \epsilon_2^1 \quad N_c = 2N \epsilon_1^1 \epsilon_2^1 \quad (7)$$

An expression for  $N = \frac{N_1 N_2}{2N_c}$  is then obtained.

The above expression for the number of radioactive transformations per second does not take into account the chance coincidences, the background coincidences, or the individual background counting rates of the counters.

The background coincidence rate and the individual background counting rates may be measured directly. The determination of the chance coincidence rate requires a knowledge of the resolving time of the coincidence circuits. Bleuler and Goldsmith (4) and Barnothy and Farro (1) have outlined a method for determining the resolving time, wherein the two counters are isolated and set to counting radiations from uncorrelated sources. The resulting coincidence counts are chance coincidences only, and the resolving time may be calculated from the expression

$N_c = 2N_1N_2\tau$ , where  $\tau$  represents the resolving time of the equipment. If the following notation is used:

$$n_1 = \text{background counts on counter number one} \quad (8)$$

$$n_2 = \text{background counts on counter number two} \quad (9)$$

$$n_c = \text{background counts on coincidence counter plus chance coincidence counts.} \quad (10)$$

The expression for the absolute decay rate then becomes:

$$N = \frac{(N_1 - n_1)(N_2 - n_2)}{2(N_c - n_c)} \quad (11)$$

## THE CHOICE OF THE PHOTOMULTIPLIER TUBE AND PHOSPHOR

Scintillation counters are no newcomers to the field of particle counting. Crookes and Regener introduced the technique of visual scintillation counting in 1908, and this type of counter has played an important role in establishing the nature and charge of the  $\alpha$ -particle.

The fact that the scintillations must be detected by the eye of a human observer places serious limitations on the above technique, however. The rate of counting is limited to about 60 scintillations per minute. In addition, only  $\alpha$ -particles can be detected by the counter, since the weak ionizations of  $\beta$ -particles and  $\gamma$ -rays do not produce scintillations of sufficient intensity to be seen by the human observer. Because of these limitations, the gas-ionization counter had largely replaced the visual scintillation counter by the late 1930's.

The years since 1947 have seen a tremendous revival of interest in the possibilities of the scintillation counter. The advances in design of reliable photomultiplier tubes that are sensitive to very small amounts of light have eliminated the necessity of the human observer and have extended the use of the scintillation counter to the study of the weakly ionizing  $\beta$ -particles and  $\gamma$ -rays.

Of the photomultiplier tubes developed in recent years, the tube that has found the widest application in scintillation counting work in this country is the RCA type 5819. The tube was developed especially for scintillation counting purposes and combines a number of desirable characteristics, two of them being a very large light sensitive surface

and a comparatively low noise level. Morton (9) and Birks (3) list detailed information on the tube. Two of these tubes were used in the equipment constructed for the present problem, the determination of the decay rates of two samples of  $\text{Co}^{60}$ .

The development of highly sensitive photomultipliers has made possible the use of many substances as phosphors. The zinc sulfide preparations used as phosphors in the visual scintillation counters have many disadvantages, some of the most serious being a long decay time for the light flash ( $10^{-5}$  seconds or longer) and a low transparency to the emitted light.

Sodium iodide crystals, activated with thallium, were used as phosphors in this work. The NaI (Tl) crystal possesses a number of properties that combine to make it a very useful phosphor. The light yield is the best of the known phosphors with the exception of  $\text{ZnS}$ , and while its decay time (about  $2.5 \times 10^{-7}$  seconds) is not as fast as some of the organic phosphors, it is still suitable for most counting work. The crystal has been shown by Hofstadter and Milton (7) to be very transparent to its emission spectrum, making possible the use of large crystals. The crystals are deliquescent, however, and must be used in air-tight surroundings. These air-tight surroundings are provided for in the case of the Harshaw crystals<sup>2</sup> by surrounding the crystal on three sides by thin aluminum and on the fourth by a transparent plastic. The "canned" crystals were taped directly to the end of the photomultipliers, with a thin

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2. The crystals are the Harshaw Scintillation Crystal, serial number 292, type 16.

film of mineral oil included to improve the optical coupling of the apparatus.

## THE ELECTRONIC CIRCUITRY

### The Photomultiplier and Preamplifier Circuit

The most frequent cause of instability in scintillation counters is the dependence of photomultiplier gain upon the applied voltage.<sup>3</sup> Unless suitable precautions are taken, any variation in applied voltage is accompanied by a large change in the counting rate.

To date there exist two methods of stabilizing scintillation counters. The first involves the use of extremely well regulated high voltage supplies with output voltages stable to about 0.01 per cent for short periods of time (hours) and 0.1 per cent for periods of days. Such stable supplies are very difficult to obtain, either commercially or by construction.

A much simpler solution to this problem is described by Sherr (10). A plateau is introduced in the gain versus high voltage characteristics of the RCA 5819 tube as a result of stabilizing the voltage between the fifth and sixth dynodes of the tube. In the circuit described by Sherr this is accomplished by means of a voltage regulator tube. Green and Paul (6) indicate that while this circuit has excellent gain characteristics, the resulting current drain on the high-voltage supply is excessive. The same effect may be obtained by the circuit of figure 1, in which the required stabilization is obtained through the use of batteries. The gain characteristics of this circuit show a slight improvement over those

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3. Green and Paul (6) state that the gain of the RCA 5819 tube is dependent upon the 8th power of the applied voltage.

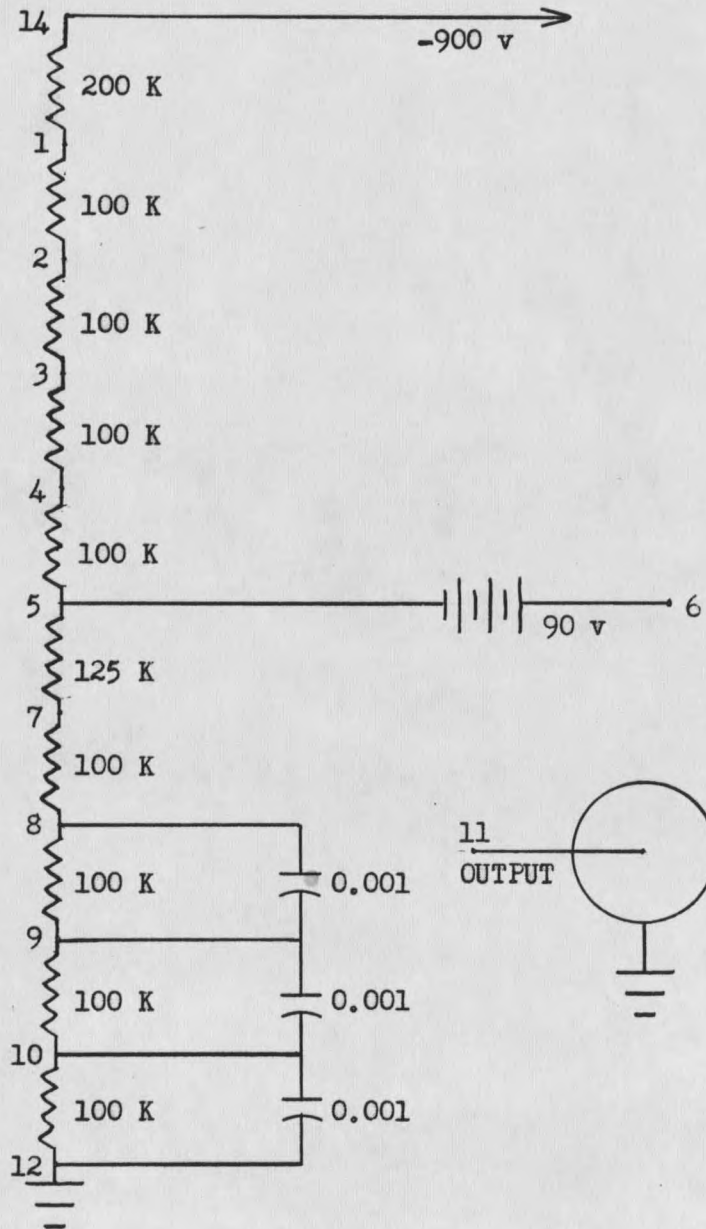


Figure 1

A Schematic Diagram of the Gain-Stabilized Photomultiplier Circuit

of the original VR tube circuit. A flat plateau extends over the range from 880 volts to 980 volts.

No theoretical basis for the existence of this plateau is offered either by Sherr or by Green and Paul. An earlier article by Morton (9) mentions the effect and attributes it to the possible occurrence of a focusing loss at the sixth dynode. The effect of the focusing loss is more pronounced at higher voltages, and partially compensates for the increased gain that accompanies higher tube voltage in a standard photomultiplier circuit.

Two of the circuits of figure 1 were constructed for the purposes of this experiment. While no extensive gain studies were carried out on these circuits, an optimum high voltage value was obtained by conducting a "counts versus high voltage" test for each photomultiplier and its associated preamplifier and amplifier. The results of these tests are shown in figure 2 and Table I.

In the process of these tests, the high-voltage measurements were made with a Triplet multimeter, Model 625-N, 10,000 ohms per volt. The meter was placed directly across the output of the high-voltage supply and remained an integral part of the circuit throughout the conduction of these and all other tests.

Figure 3 shows the complete schematic diagram for the photomultiplier and preamplifier unit, and figure 4 shows the diagram for the amplifier and coincidence unit.

The cathode follower preamplifier provides the necessary impedance

TABLE I

Results of Tests on Plateau Region in Gain Characteristics of  
Photomultiplier Tube

Volts	Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64
820	37	65
840	108	98
860	153	129
890	163	137
910	167	137
930	174	126
940	169	127
955	231	121

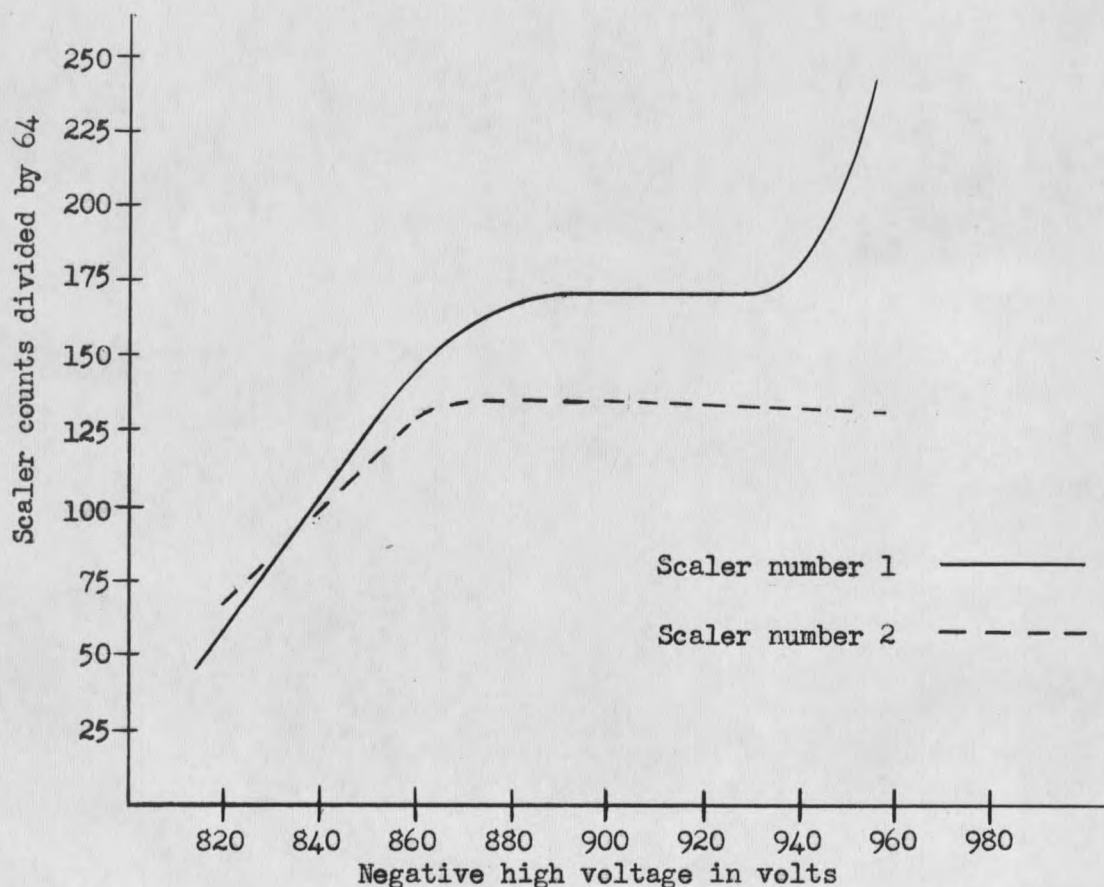


Figure 2. A plot of scaler counts vs. negative high voltage.

match between the photomultiplier and the coaxial cable used to couple to the main amplifier.

The Amplifier and Coincidence Circuit

The amplifier consists of a series of 12AU7 twin triodes and incorporates the principle of direct coupling throughout. The schematic diagram for this amplifier was furnished by Mr. W. Farrand of Richland, Washington. Complete information as to its performance was not available at the time and has not been published since. However, the amplifier was reputed to possess excellent discrimination control and stability.

The two amplifier units constructed by the author did not give the performance that had been anticipated. The 50-ohm potentiometer which supposedly provides the discrimination control had no discernable effect on the counting rate. The counting rate was very dependent upon the supply voltage, with higher counting rates occurring at lower supply voltages. In addition, a pronounced drift in counting rate appeared in one of the units, although the other could be depended upon to provide consistent results. The reputation of the amplifier is well established however, and these unfortunate characteristics can only be attributed to faulty construction and/or faulty components, although thorough tests on the components indicated that they were in good condition.

The nature of the output pulses from the two amplifier stages (very uniform pulse amplitude, sharp leading and trailing edges, 50 volt amplitude, less than 1 micro-second pulse width) was felt to be sufficient

advantage to warrant the use of the amplifiers. Such uniform, high-voltage pulses made the design of the coincidence network a simple matter.

The coincidence circuit used was of the Rossi type, using a twin-triode 6J6 tube. The action of the circuit may be described as follows. A signal (negative) from one of the amplifiers will cut off one-half of the tube. The resultant tendency for a reduced current through the common-cathode resistor, R25, reduces the grid to cathode voltage for the other section of the tube. The conduction of this half of the tube then increases, and the effect is one of negative feedback for a signal from only one amplifier. If, however, simultaneous signals from both amplifiers are present at the grids of the coincidence tube, both halves are cut off and a large negative-going pulse appears across the cathode resistor R25 (figure 4).

The ratio of the output resulting from coincident pulses to that resulting from non-coincident pulses for the circuit shown in figure 4 is 2.5/1. While this value does not compare with the 10/1 ratio obtainable from some Rossi-type circuits, the use of additional discriminating stages has increased the ratio to 25/1. Coincident pulses result in a negative-going pulse across resistor R34 of 125 volts, whereas non-coincident pulses result in signals of only 5 volts. The output from the coincidence circuit is reduced by resistors R35 and R36 to a value consistent with the requirements of the scaler units. The outputs from the amplifiers are reduced in the same fashion.

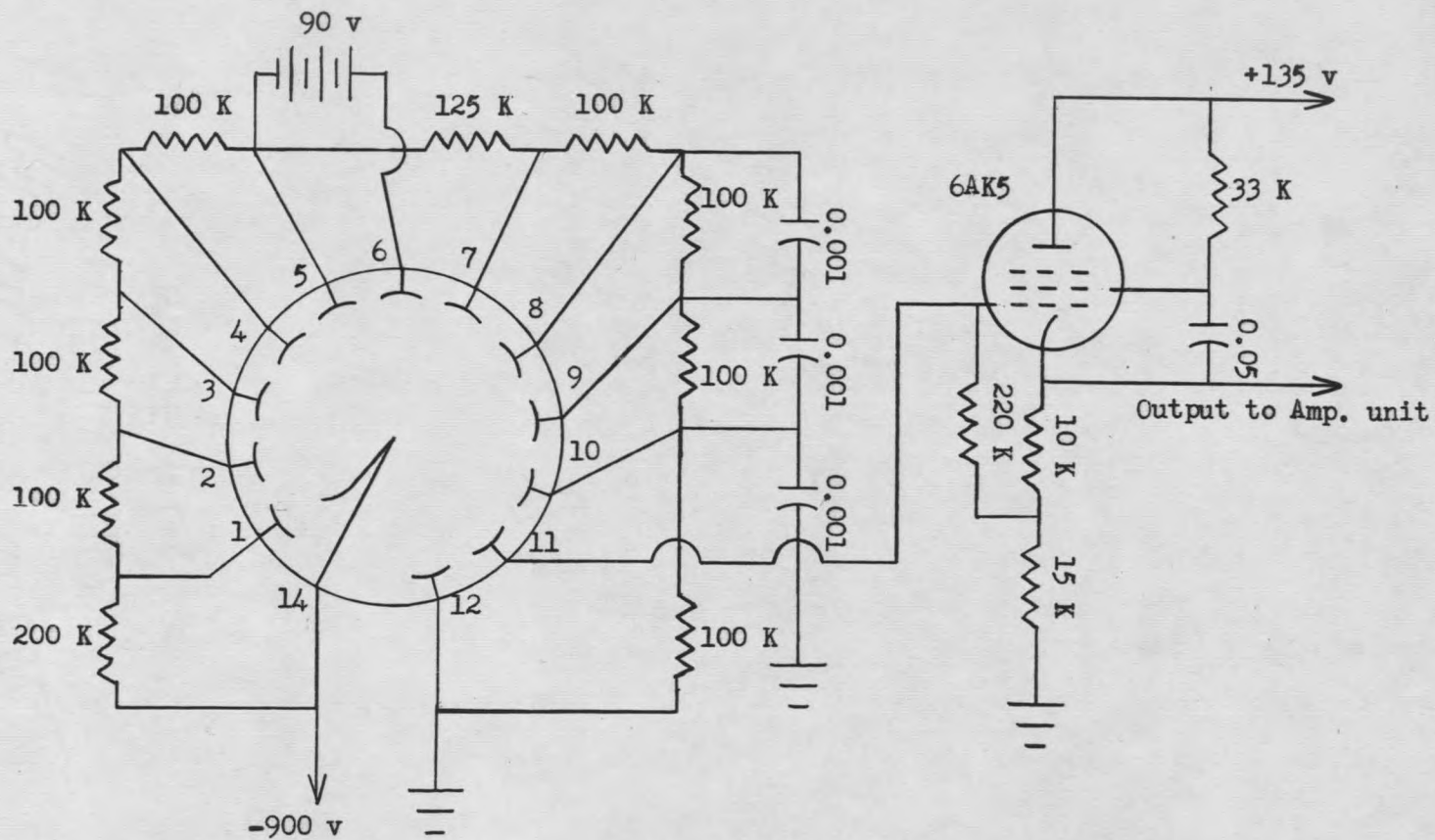


Figure 3. Schematic Diagram of the Photomultiplier and Preamplifier Circuit

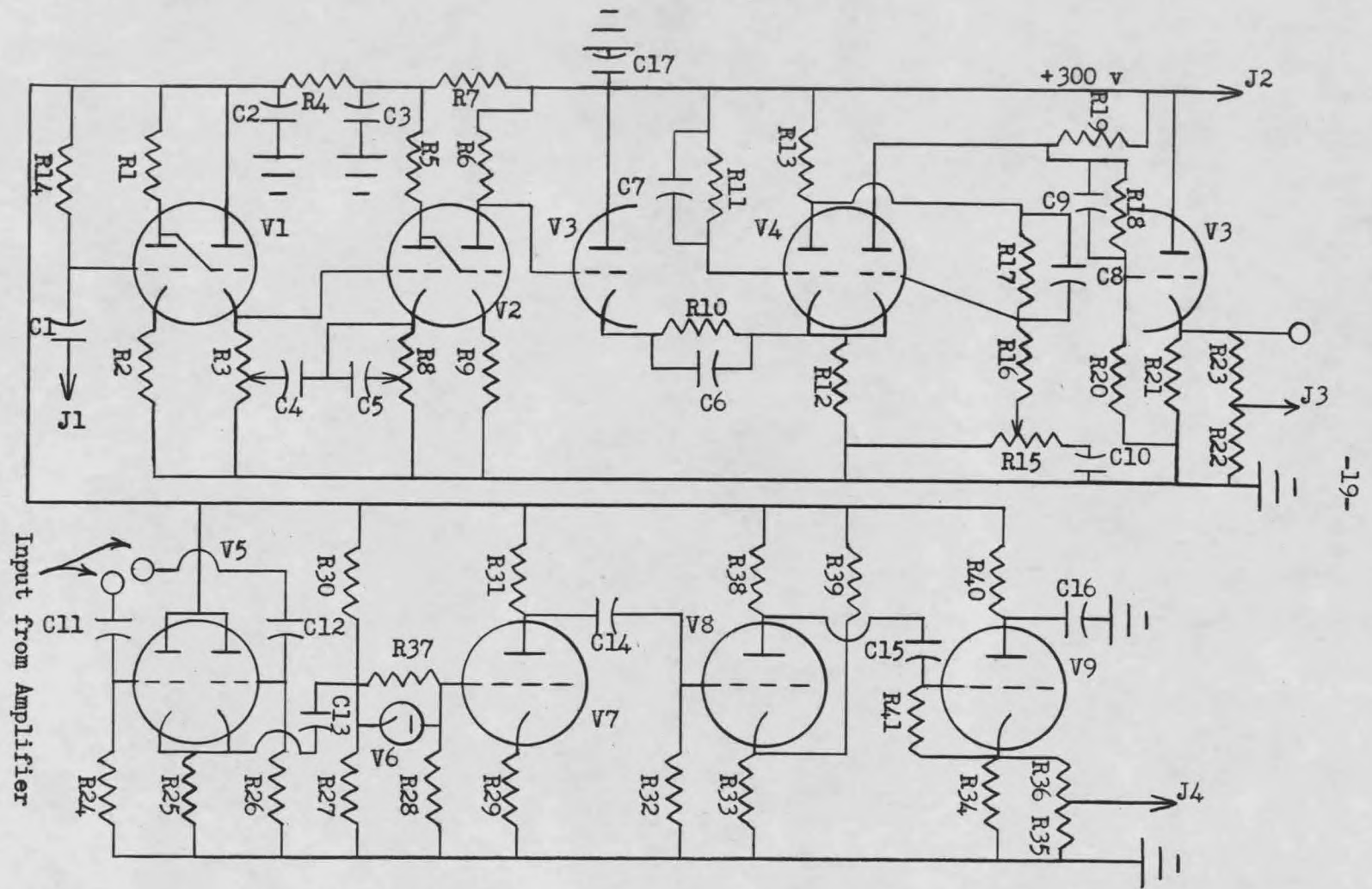


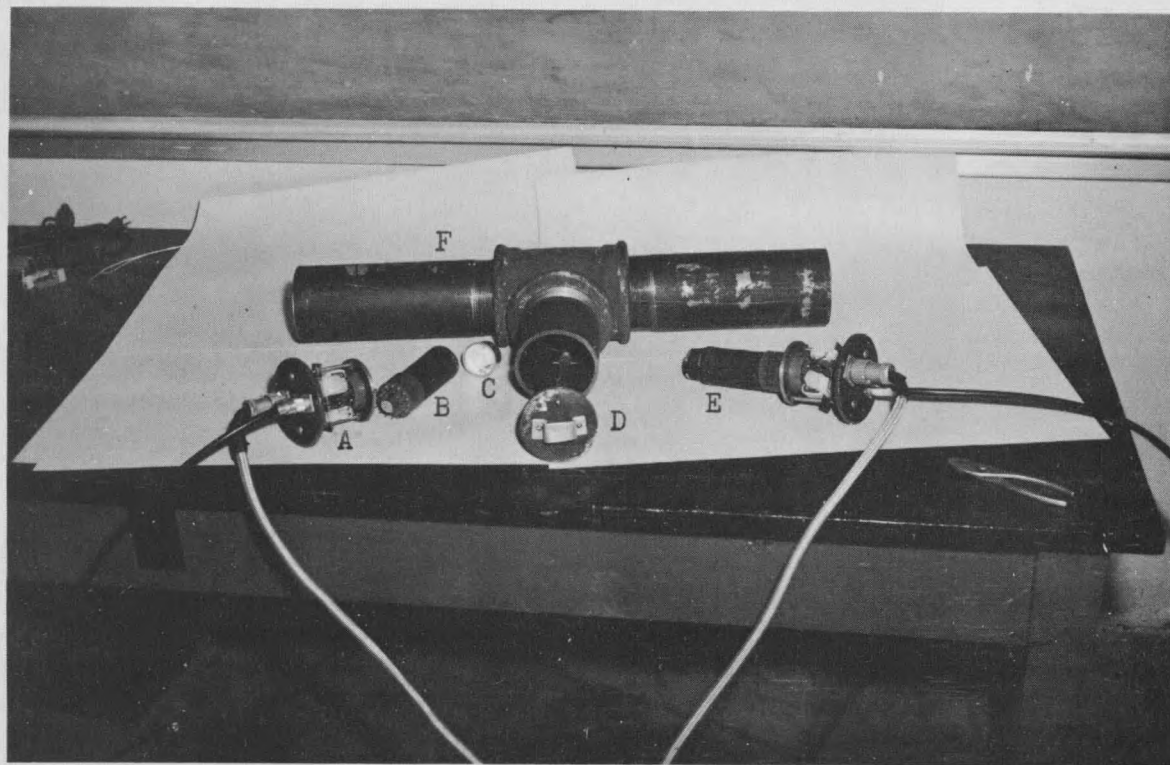
Figure 4. Schematic Diagram of the Amplifier and Coincidence Circuits

### DESCRIPTION OF EQUIPMENT

Figures 5 and 6 are photographs of the equipment. Figure 5 is an exploded view of the test chamber. The chamber was constructed of four-inch iron pipe having walls one-fourth inch thick. The chamber provided some shielding from stray radiation and a rigid, protective support for the sample and the photomultiplier probes. The shielding effect was of little value in the conduct of the tests, however, since in the research room used the shielded background rate was as high as the unshielded background rate, indicating that the background was due primarily to penetrating cosmic radiations.

The sample holder consisted of a long, thin rod of polystyrene, with a grooved end to hold the ampules containing the  $\text{Co}^{60}$  samples.

The penetrating nature of the gamma radiation of  $\text{Co}^{60}$  made possible the complete covering of the photomultiplier and crystal detectors with a light tight layer of Scotch electrical tape. The aluminum "cans" used to preserve the NaI (Tl) crystals introduced no difficulties, since the absorption of gamma rays by such a thin layer of aluminum is not appreciable. One of the probe assemblies is shown in a dismantled form in the photograph.



- A - The photomultiplier and preamplifier mount.
- B - The photomultiplier tube.
- C - The NaI (Tl) crystal.
- D - The sample holder.
- E - The preamplifier, photomultiplier, and crystal as assembled for the tests.
- F - The test chamber.

Figure 5. An exploded view of the test chamber.

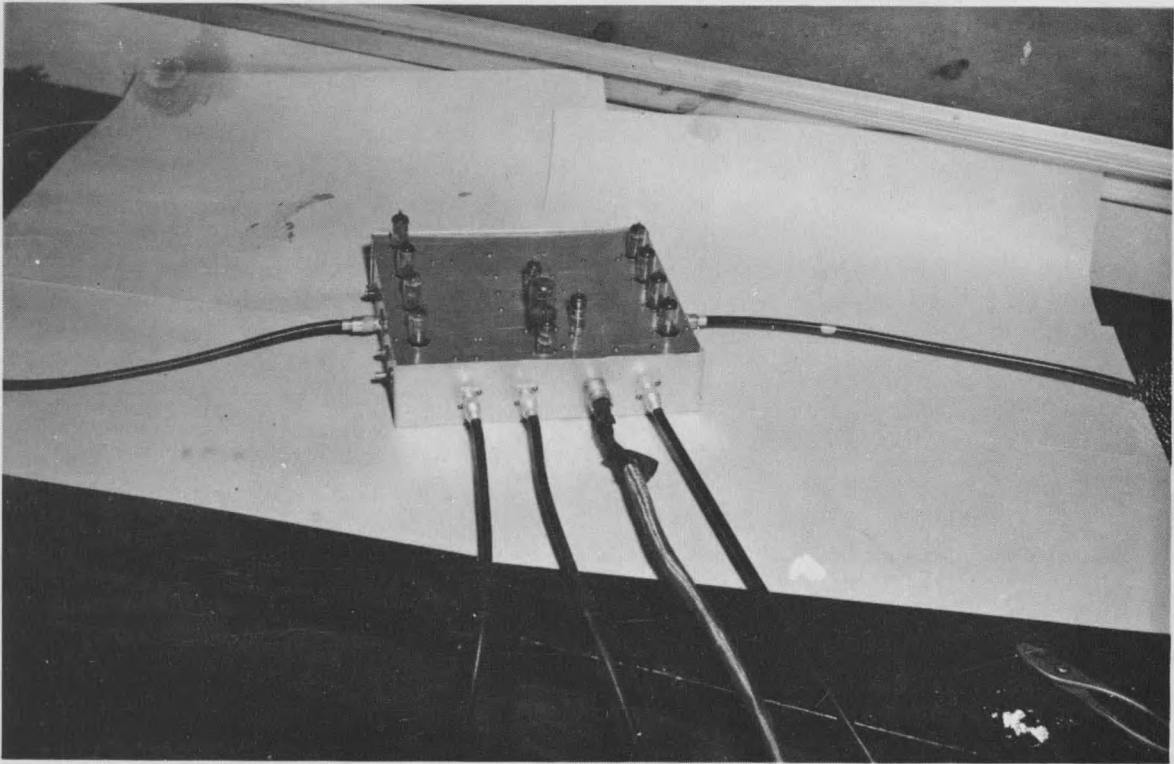


Figure 6. A photograph of the amplifier and coincidence unit.

### THE TESTS ON THE LOW-ACTIVITY SAMPLE

The first series of tests was conducted to determine the absolute decay rate of a sample labeled  $\text{Co}^{60}$  (0.1 rd.). This sample was obtained from the Bureau of Standards and was calibrated by that Bureau in July of 1947. The activity of the sample was determined to be 0.159 rd., or  $1.59 \times 10^5$  radioactive decays per second, on July 24 of that year.

The tests conducted to determine the decay rate of this sample were the following:

1. The determination of the background level for each of the three counters.
2. The determination of the resolving time of the coincidence circuit by counting isolated sources.
3. The determination of the absolute decay rate of the sample from the total number of counts of the three counters with the sample in place.

Ten tests of one-half hour duration were run to determine the various background counting rates. Successive counts of counter number one were very consistent, although over the total counting period of five hours, a slight drift towards higher counting rates was observable. Successive counts on counter number two showed a wider spread (a variation from  $118 \times 64$  to  $114 \times 64$  in the extreme case) but no drift in counting rate was apparent.

The number of background coincidence counts varied around a mean value of 1.9 counts per half hour. Ten tests were perhaps inadequate to

establish this mean value to any considerable degree of certainty, but the significance of the background in establishing the decay rate is small.

A 5 per cent error in coincidence background would influence the final result by less than 0.2 per cent. These test results are shown in Table II.

A series of twelve tests of fifteen minutes duration each was conducted to determine the resolving time of the coincidence circuit. These tests were carried out at approximately the same counting rates as the tests to determine the absolute decay rate so that no errors would be introduced due to a dependence of resolving time on the counting rate. The results of the tests are shown in Table III.

Fifty tests of 15-minute time duration were conducted to determine the absolute decay rate of the  $\text{Co}^{60}$  sample. The results of the tests are shown in Table IV.

The variation in the number of coincidence counts was quite large, and a longer test period might seem to be indicated. It was felt that, while the longer test period was desirable from a statistical viewpoint, the use of such a period would introduce errors of a magnitude that could not be readily evaluated. The validity of the derivation of equation 11 depends on the constant nature of the probabilities of detection of the particles by the counters.

Previous mention has been made of the fact that one of the counters (counter number one) evidenced a pronounced drift in counting rate, indicating a time variation in probability. It appeared possible to keep the counting rate constant over 15-minute periods so this test period was used.

TABLE II

Background Tests

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts
87	116	2
86	117	1
87	117	2
87	118	0
87	114	3
87	114	2
88	116	0
91	114	2
90	116	3
90	114	4

TABLE III

Results of Resolving Time Tests

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	Resolving Time in seconds $\times 10^{-7}$
848	1919	6	4.05
854	1930	16	10.65
810	1960	12	8.29
806	1945	13	9.10
841	1943	8	5.37
847	1883	9	6.23
884	1905	8	5.21
870	1885	5	3.35
901	1899	13	8.34
911	1899	13	8.25
912	1903	10	6.33
922	1882	8	5.06

TABLE IV

Results of the Activity Tests on the Low Activity Sample

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	No. Decays per second $\times 10^{-4}$
758	647	13	10.12
756	634	24	4.55
762	642	14	9.13
770	625	20	5.65
791	639	19	6.43
792	639	19	6.44
791	640	19	6.44
791	647	14	9.69
742	652	17	7.00
754	652	12	11.36
740	642	12	10.83
744	643	19	6.01
744	643	19	6.01
744	645	18	6.45
748	645	19	6.08
748	645	19	6.08
748	645	19	6.08
766	647	15	8.47
766	640	18	6.62
763	630	20	5.68

TABLE IV (Cont'd.)

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	No. Decays per second $\times 10^{-4}$
751	637	22	5.04
757	624	13	9.51
763	634	16	7.55
758	630	15	8.07
774	640	16	7.79
741	634	16	7.46
809	588	20	5.63
809	588	21	5.31
723	603	21	4.79
723	603	14	7.90
722	604	15	7.23
767	603	15	7.80
703	614	21	4.73
705	604	16	6.47
705	604	17	6.00
706	604	17	6.00
757	605	17	6.12
768	609	19	5.88
776	618	13	9.88
753	625	18	6.34
761	609	24	4.41

TABLE IV (Cont'd.)

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	No. Decays per second $\times 10^{-4}$
809	588	13	6.87
756	648	24	4.72
844	668	22	6.21
720	660	22	5.04
770	665	19	6.60
788	657	17	7.69
774	660	23	5.22
763	654	20	6.00

### TESTS WITH THE HIGH-ACTIVITY SAMPLE

The tests conducted to determine the decay rate of a sample labeled  $\text{Co}^{60}$  (1 rd.) paralleled those conducted on the less active sample. No background rates were obtained other than to verify that these rates were approximately the same as in the previous series of tests, since the background rates affected the final results much less than before.

The resolving time tests and the decay rate tests were shortened to three minutes from the fifteen minutes used for the other sample. The primary reason for this change of procedure was to reduce the overall time of testing. The much higher coincidence counting rate involved here (more than ten times as high) indicated that the results for this sample should be at least as reliable as those obtained for the lower activity sample.

Since the number of chance coincidences represented a much larger portion of the total number of coincidences than previously (about 70 per cent of the total as compared to about 12 per cent), it was felt that a much more accurate measure of the resolving time was in order. The number of resolving time tests was increased to forty to reduce the probable error of the final average value. The two values obtained for the resolving time agree to within 3.5 per cent, indicating that the counting rate had little effect on the resolving time.

The results of the various tests are shown in Tables V and VI.

TABLE V

Resolving Time Tests  
(1.0 rd Sample)

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	Resolving Time in seconds x 10 <sup>-7</sup>
1430	1220	60	7.55
1417	1212	58	7.42
1420	1226	51	6.43
1406	1215	62	7.97
1432	1232	61	7.60
1434	1237	47	5.82
1417	1209	45	5.73
1420	1214	65	8.28
1419	1213	59	7.53
1434	1223	50	6.26
1432	1227	48	6.00
1351	1226	58	7.69
1395	1224	49	5.95
1386	1209	52	6.81
1407	1218	56	7.17
1429	1225	64	8.03
1395	1223	56	7.21
1389	1228	64	8.24
1391	1216	47	6.11
1399	1210	58	7.52

TABLE V (Cont'd.)

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	Resolving Time in seconds $\times 10^{-7}$
1399	1216	54	6.97
1417	1213	44	5.62
1383	1218	52	6.78
1393	1224	49	6.31
1396	1221	42	5.42
1394	1210	63	8.20
1387	1210	50	6.58
1389	1216	56	7.28
1391	1212	44	5.73
1375	1211	54	7.12
1574	1213	48	5.53
1481	1216	62	7.56
1421	1211	50	6.38
1407	1210	65	8.39

TABLE VI

Activity Tests  
(1.0 rd Sample)

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	No. Decays per second x 10 <sup>-5</sup>
1471	1225	112	3.61
1489	1227	82	8.13
1431	1235	100	4.39
1437	1232	93	5.24
1433	1225	75	9.65
1541	1244	105	4.74
1563	1217	94	6.14
1541	1230	107	4.43
1526	1218	88	6.91
1538	1203	93	5.86
1557	1226	107	4.50
1547	1218	92	6.33
1532	1193	86	7.05
1537	1211	88	6.94
1553	1215	93	6.17
1558	1206	102	4.85
1534	1171	82	7.72
1554	1160	82	7.81
1597	1221	91	7.22
1448	1210	79	8.02

TABLE VI (Cont'd.)

Counts, Scaler No. 1 Divided by 64	Counts, Scaler No. 2 Divided by 64	Coincidence Counts	No. Decays per second $\times 10^{-5}$
1429	1189	91	4.99
1476	1215	89	6.00
1398	1206	86	5.62
1412	1210	80	7.15
1421	1204	93	4.82
1418	1208	83	6.47
1435	1212	101	4.16
1442	1215	76	9.14
1421	1207	82	6.70
1438	1212	78	8.21
1463	1210	79	8.31
1400	1208	84	6.04
1404	1226	77	8.21
1404	1213	89	5.41
1422	1206	83	6.50
1412	1199	77	7.81
1423	1209	87	5.75
1413	1202	88	5.41
1435	1211	86	6.11
1469	1234	70	15.0

### DISCUSSION OF RESULTS

The average value for the number of decays per second obtained from the series of tests on the  $\text{Co}^{60}$  (0.1 rd.) sample was  $6.78 \times 10^4$  decays per second. The calibration by the Bureau of Standards on July 24, 1947 placed the activity of the sample at 0.159 rd. or  $1.59 \times 10^5$  decays per second.

The expected value for the number of decays per second is obtained by substituting the appropriate value of  $t$  into the expression  $N = N_0 e^{-\lambda(t-t_0)}$ . In this expression,  $N_0$  represents the number of atoms of the radioactive material present at the time  $t_0$ ,  $N$ , the number of atoms present at time  $t$ , and  $\lambda$ , the decay constant. The decay constant  $\lambda$  is equal to the fraction of the total number of atoms that decay per unit time. Its value for a specific radioactive substance is obtained from the half life ( $\tau$ ) of the substance as follows:

$$\frac{1}{2}N_0 = N_0 e^{-\lambda\tau}$$

$$\lambda = \frac{\ln 2}{\tau}$$

Since the number of radioactive decays per second is proportional to the total number of atoms present, one may interpret the symbols  $N_0$  and  $N$  as the number of decays per second at the times  $t_0$  and  $t$ .

The value for the half life of  $\text{Co}^{60}$  given by Lapp and Andrews (8) is 5.26 years. Thus the expected value for the number of decays per second of the sample is  $6.68 \times 10^4$  dps. The tests were performed on March 15, 1954. The Bureau of Standards value has a probable error of not more

than 2 per cent. The experimental value of  $6.78 \times 10^4$  lies within this 2 per cent range.

The tests on the more active sample were conducted on March 26, 1954, and a mean value of  $6.59 \times 10^5$  was obtained for the number of decays per second. Again this value is within the 2 per cent range specified on the Bureau of Standards certificate. This sample was also calibrated on July 24, 1947, and its activity placed at 1.59 rd. The expected value is  $6.65 \times 10^5$  dps.

While the above results are in good agreement with the expected values, they do not take into consideration two sources of error. These errors can be expected to compensate for one another to some extent, although it is difficult to state the exact extent. The two sources of error are any directional correlations that might be involved in the decay of the sample, and the existence of satellite after-pulses in the photomultiplier tubes.

Fairly accurate information is available concerning the directional correlation of the gamma rays emitted by  $\text{Co}^{60}$ . On the basis of this information, Barnothy and Farro (1) predict that the probability of a coincidence count with an angular separation of  $180^\circ$  between the detectors exceeds the probability of a coincidence count in the  $90^\circ$  direction by about 16 per cent. The resultant error in a determination of the absolute decay rate is shown to be 9.2 per cent. The experimental value will be smaller than the actual value.

No such concrete information is available concerning the effect of

after-pulsing. All evidence to date indicates that the effect is present in varying degrees in all photomultipliers. Birks (3) states that the satellite after-pulses associated with the RCA 5819 tube might extend over a period of 8 micro seconds but gives almost no information concerning the height of the pulses.

From the standpoint of statistical reliability, the results obtained from the various tests are quite consistent. The standard deviation of the values obtained for the activity of the less active sample is  $1.66 \times 10^4$  decays per second. With this value of standard deviation, the probable error in the mean value of  $6.78 \times 10^4$  decays per second is not greater than  $\pm 2.3$  per cent. The standard deviation of the results of the test on the more active sample is  $1.49 \times 10^5$  decays. In this case the probable error in the average value of  $6.59 \times 10^5$  decays per second does not exceed  $\pm 2.4$  per cent.

### CONCLUSIONS

The results of the tests on the two Co<sup>60</sup> samples indicate that scintillation counters may be applied to the problem of determining the absolute decay rate of a radioactive material. As is the case with Geiger-Müller tubes, considerable information must be available concerning the decay scheme of the substance.

The most significant advantage resulting from the application of scintillation counters to this problem lies in the greater sensitivity of this type of counter to gamma rays. The total time required for any desired statistical accuracy is primarily dependent upon the coincidence counting rate, which in turn is determined to some extent by the sensitivity of the detectors to the radiation in question.

The only disadvantage resulting from the use of scintillation counters would seem to be the difficulty in determining the effects of the after-pulsing characteristics present in all photomultipliers. More complete information on this subject will perhaps permit the design of pulse-discrimination circuits that will remove this difficulty.

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APPENDIX

PARTS LIST FOR THE CIRCUIT SHOWN IN FIGURE 4

R1 - carbon resistor - 22 K	C1 - 460 $\mu$ f
R2 - " " - 100 K	C2 - 0.1 $\mu$ f
R3 - gain control potentiometer - 4.7 K	C3 - 0.1 $\mu$ f
R4 - carbon resistor - 10 K	C4 - 0.1 $\mu$ f
R5 - " " - 33 K	C5 - 0.1 $\mu$ f
R6 - " " - 33 K	C6 - 0.005 $\mu$ f
R7 - " " - 2.7 K	C7 - 50 $\mu$ f
R8 - gain control potentiometer - 10 K	C8 - 0.001 $\mu$ f
R9 - carbon resistor - 39 K	C9 - 0.002 $\mu$ f
R10 - " " - 33 K	C10 - 0.1 $\mu$ f
R11 - " " - 220 K	C11 - 470 $\mu$ f
R12 - " " - 2 K	C12 - 470 $\mu$ f
R13 - " " - 18 K	C13 - 470 $\mu$ f
R14 - " " - 470 K	C14 - 470 $\mu$ f
R15 - discrimination control potentiometer - 50 $\Omega$	C15 - 470 $\mu$ f
R16 - carbon resistor - 10 K	C16 - 0.1 $\mu$ f
R17 - " " - 100 K	
R18 - " " - 470 K	V1 - 12AU7 twin triode
R19 - " " - 4.7 K	V2 - " " "
R20 - " " - 100 K	V3 - " " "
R21 - " " - 6.8 K	V4 - " " "
R22 - " " - 10 K	V5 - 6J6 twin triode
R23 - " " - 100 K	V6 - 6H6 twin diode wired in parallel
R24 - " " - 100 K	V7 - 6J6 twin triode wired in parallel
R25 - " " - 18 K	V8 - 6J6 twin triode wired in parallel
R26 - " " - 100 K	V9 - 6J6 twin triode wired in parallel
R27 - " " - 100 K	
R28 - " " - 100 K	J1 - input from photomultiplier and preamplifier probe
R29 - " " - 200 K	J2 - B+ input
R30 - " " - 2 Meg	J3 - output to scaler unit from amplifier unit
R31 - " " - 22 K	J4 - output to scaler unit from coincidence unit
R32 - " " - 100 K	
R33 - " " - 22 K	
R34 - " " - 4 K	
R35 - " " - 44 K	
R36 - " " - 1.2 Meg	
R37 - " " - 2 Meg	
R38 - " " - 22 K	
R39 - " " - 75 K	
R40 - " " - 4 K	
R41 - " " - 150 K	

