Rasetti's experiment, $v_a=2200$ meters/sec., $u=140$ m/sec., and $\Delta p/p=6.3$ percent. From (7):

$$\epsilon=0.09_5 \text{ ev.} \tag{8}$$

Inserting (6) and (8) in (3), (4), we obtain:

$$E_r=0.18 \text{ ev}, \quad \Gamma=0.15 \text{ ev}. \tag{9}$$

This result is, unfortunately, very sensitive to small errors in $\Delta p/p$ as can be seen from an inspection of (7). If ϵ is changed to 0.11 ev, the result is that $E_r=0.17$ ev and $\Gamma=0.19$ ev. With the present measurements it seems that E_r and Γ are of the same order of magnitude and are both about 0.15 ev. Bethe and Placzek[11] have made calculations using Amaldi and Fermi's data[7] on the absorption of "D" neutrons in Cd and find $E_r=0.14$ ev and $\Gamma=0.20$ ev. According to Eq. (9) the experimental ratio $\Gamma/E_r=0.80$, which would correspond to the case of a fairly pronounced resonance hump in the curve of cross section plotted against E/E_r as given by Bethe and Placzek. The figures calculated by Bethe and Placzek give $\Gamma/E_r=1.42$ approximating the case $\Gamma/E_r=\sqrt{2}$ which has a less pronounced resonance hump and a region of almost constant cross section as the energy varies from 0.05 to 0.12 ev.

[11] Bethe and Placzek, Phys. Rev. **51**, 450 (1937).

From the values given in (9) an estimate may be made of the neutron width according to the calculations of Bethe and Placzek[11]

$$\Gamma_N=\frac{E_r\kappa_r\Gamma_{\text{eff}}}{1.23\times 10^3}, \tag{10}$$

where κ_r is the absorption coefficient at resonance and Γ_{eff} is the effective cross section which may be replaced by $\pi\Gamma$ if the natural width, Γ, is large compared with the Doppler width. κ_r is about 1.3 times the absorption coefficient at thermal energies. Thus $\Gamma_N=(1.3E_r\kappa_r\pi\Gamma)/1.23\times 10^3$ and $\Gamma_N=1.3\times 10^{-3}$ ev.

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Production, Characteristics, and Reliability of Geiger-Müller Counters*

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A technique for the production of reliable Geiger-Müller counters is described. By the use of pure hydrogen gas and by cleaning the electrodes by sputtering in a glow discharge in hydrogen previous to filling the tubes with hydrogen gas, tubes with plateaus of 400 volts are produced. Copper, nickel, and tungsten have been found suitable for cathode cylinders while aluminum was not. Tubes filled with pure argon, pure oxygen, or air were found to give many spurious counts. An extensive series of reliability tests is described which shows that carefully made counter tubes used in properly designed circuits give completely reliable quantitative data.

THE use of Geiger counters for quantitative measurements on natural and artificial radioactivity has been practically abandoned because they have been found to be unreliable. However, their many advantages made it seem desirable to investigate the characteristics of the tubes and the circuits in an effort to develop reliable counting apparatus. Consequently, a systematic study has been made of the electric discharges in the tubes and of the characteristics of the electric circuits. The variations in the constants and the characteristics of the discharges produced by changing the electrode materials and the gas were investigated. Observations were made on the effects of impurities on the surface of the cathode and in the gas. After a

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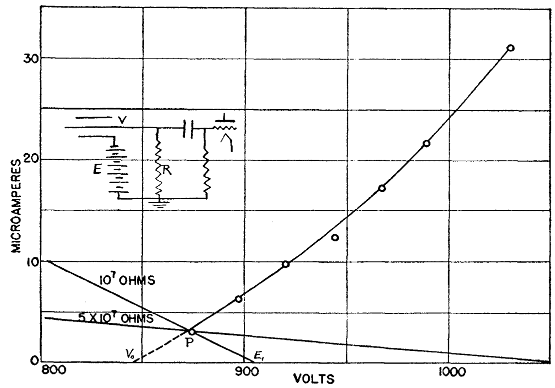

FIG. 1. The corona characteristic of a Geiger-Müller counter tube and diagram of a conventional circuit.

technique for making tubes of the desired characteristics had been developed and properly designed circuits had been built, a series of reliability tests was made. These tests show that properly made counters used in properly designed circuits give reproducible and reliable data.

First, the type of discharge produced in a Geiger counter tube was identified as the corona. Some of the experiments of Werner[1] were repeated and these confirmed his conclusion that the essential characteristic of the discharge which makes it adaptable for counting is that, with weak ionizing radiation, the discharge is not self-maintaining when the current falls below a minimum value characteristic of the tube. The value of the current and the voltage at the minimum point determine for a given circuit the range of voltage over which counting is possible; the larger the minimum current, the longer the counting range, as was pointed out by Werner. A consideration of Fig. 1 will make this clear and will likewise emphasize inherent weaknesses in the conventional circuit that has been widely used with Geiger-Müller counter tubes.

The conventional circuit employed is sketched as an insert in Fig. 1 and consists of a battery, or other source of d.c. e.m.f., with a tube and high resistance in series. The tube has concentric cylindrical electrodes. The anode is a fine tungsten wire and is connected to the grid of a vacuum tube by resistance-capacity coupling. We shall be concerned only with the series circuit containing the tube, quenching resistance, and source of e.m.f. Except when ionization is produced in the tube following the passage of a β-particle or γ-ray, the current through the tube is substantially zero, and the difference of potential between the electrodes is equal to the e.m.f. of the circuit. When a current is maintained, two equations must be satisfied simultaneously:

$$V=f(i), \qquad (1)$$

$$V=E-Ri, \qquad (2)$$

where V is the voltage across the tube, E the e.m.f. of the circuit, R the resistance, and i the current in the circuit.

Equation (1) is the corona characteristic and is plotted for a hydrogen filled, tungsten cathode Geiger-Müller counter tube in Fig. 1. V_0 is the minimum corona voltage. P is the minimum point for the corona under the influence of the weak radiation irradiating the tube; its coordinates represent the minimum voltage and current for a sustained discharge. Eq. (2) is represented by the straight line in the figure, and it will be noted that the slope of this line is determined by the resistance of the circuit which is practically equal to the high quenching resistance, R. Two lines representing Eq. (2) are drawn through the, minimum point for a self-maintained discharge and so the voltage intercepts represent the minimum e.m.f.'s that will maintain a discharge in the tube with the amount of quenching resistance shown on each line. For a given resistance, lines for larger values of the e.m.f. would be parallel to the one shown and would intercept the corona characteristic at points above the minimum point and thus would maintain a discharge in the tube. On the other hand, lines for smaller e.m.f.'s would intersect the characteristic below the minimum point and therefore would not maintain a discharge. The e.m.f. in the circuit under these conditions is the "operating voltage" of the tube, as the tube voltage has this value except for the brief intervals during which there is a discharge.

The voltage at which counting begins is not much above V_0 and the maximum voltage at the counting range is the value, E_1, of the voltage intercept of Eq. (2) for the line which passes

[1] S. Werner, Zeits. f. Physik **90**, 384 and **92**, 705 (1934). See also Evans and Mugele, Rev. Sci. Inst. **7**, 441 (1936). Henning and Schade, Zeits. f. Physik **90**, 605 (1934); von Hippel, Zeits. f. Physik **97**, 455 (1935); Schulze, Zeits. f. Physik **78**, 92 (1932) and references given therein.

through P, for at higher voltages a continuous discharge is maintained. Suppose the operating voltage is less than E_1. When an electron is set free in the electric field of the tube a sequence of events is started, including ionization of gas molecules and the liberation of electrons from the cathode, which results in an avalanche of electrons coursing toward the anode. The collection of these electrons causes a reduction in the anode potential while they escape slowly through the quenching resistance. Positive ions are simultaneously drawn toward the cathode, but they move more slowly than the electrons. The result of the collection of these charged particles is a current through the resistance R and a change in the condition of the circuit toward the equilibrium condition for a sustained discharge represented by the intersection of the two curves representing Eqs. (1) and (2). As this is below the minimum point, the discharge breaks, but the potential of the center wire has been reduced momentarily from E to some value near V_0, and so a voltage pulse is produced which causes a reaction in the amplifying circuit coupled with the counter tube and the recording of a count. For a given circuit, the amplitude of voltage pulse necessary to produce a count must exceed a certain minimum, and so the operating voltage must exceed V_0 by this small amount before counting begins. Counting is thus observed to begin after the operating voltage has been raised above V_0 a few volts and will continue until the operating voltage is increased to E_1, but the so-called plateau will consist of only a portion of this counting range for reasons to be given later.

It will be obvious from the reasoning given above and from a consideration of Fig. 1 that the extent of the counting range may be increased by increasing the quenching resistance R. The counting range has the value of approximately $i_{\min} R$. As shown by the curves, the counting range of the counter illustrated is increased from about 50 to 250 volts by increasing the resistance from 10^7 to 5.10^7 ohms.

But an increase in the quenching resistance increases the relaxation time of the circuit containing the tube in direct proportion, as this time is given by the product of the resistance and the capacitance of the circuit. When large resistances are necessary, the relaxation time becomes so large that an excessive loss of counts results, and the apparatus becomes useless for quantitative measurements. This cause alone is a sufficient reason why Geiger-Müller counters used in the conventional circuits are not suitable for collecting quantitative data in nuclear physics and came to be mistrusted by many research workers.

The counting range is also proportional to the minimum current of a sustained discharge, as a glance at Fig. 1 reveals. Therefore it is important to make tubes having large values of $i_{\min}$. Measurements on a number of small air-filled tubes showed that $i_{\min}$ often had a value of less than one microampere. In order to have an adequate counting range, the quenching resistance used with these tubes had to be of the order of 10^9 ohms and the relaxation time of the tube circuit under these conditions was of the order of one hundredth second, much too large for accurate counting. Hydrogen-filled tubes of the same size with well-cleaned electrodes of copper, nickel, or tungsten were found to have minimum maintaining currents of 3 to 5 microamperes, and so could be operated with correspondingly smaller quenching resistances.

The proper solution of the difficulty arising from a long relaxation time, and the one adopted by the writers and being rapidly adopted by others, is to replace the quenching resistance by a properly designed vacuum tube circuit. Several circuits have been successfully used. We have adopted the Neher-Harper[2] circuit and found it completely dependable. It requires a resistance of only from 10^6 to 10^7 ohms through which the collected electrons flow, and so the relaxation time is greatly reduced, having now the value of 10^{-4} to 10^{-5} seconds. The limitation of the speed of counting is now mainly in the thyratron operated recorder circuit. Good Geiger-Müller tubes used in a Neher-Harper circuit coupled to a scale of eight circuit built up with vacuum tubes instead of thyratrons have been found to show no losses when counting at the rate of 2000 counts per minute. Such a circuit has recently been developed in this laboratory by one of us (H. L.) and Mr. J. L. Lawson and will be described in a subsequent publication. The limitation to about 2000 counts per minute is, in fact, imposed by the

[2] Neher and Harper, Phys. Rev. **49**, 940 (1936).

Cenco recorder used. A higher scale counter will increase the rate of counting without loss. The circuit constants would permit 30,000 counts per minute or more.

It is desirable for the Geiger-Müller tube to have a relatively high minimum maintaining current, 3 to 5 microamperes, and it is essential to reliable counting for the tube to have a definite minimum point. Observations on a number of tubes indicate that this is not always the case and that impurities in the gas and unclean electrodes are the principal causes for lack of definiteness of this point. Consequently we developed a technique for making tubes that has produced uniformly good tubes with very sharp and definite minimum points.

The tubes are made in pairs, and after two of them have been sealed onto a vacuum system, they are exhausted while being heated with a soft flame until a good vacuum is obtained. The electrodes should be thoroughly outgassed by using an induction furnace or otherwise. Then hydrogen is admitted to a pressure of 2 to 7 mm and an a.c. glow discharge is produced between the cathode cylinders of the two tubes by means of a small neon sign transformer. The tubes are made in pairs because the fine center wire might be melted if it were used as one of the electrodes of the glow discharge. As the gas becomes contaminated, it is pumped out and replaced by fresh hydrogen. Care must be taken to disconnect the transformer during the exhaustion when tubes with thin windows are being made as these may be punctured by the discharge at low pressures. This process is repeated until the electrodes are sputtered clean and bright and the gas is spectroscopically pure. During the later stages, the center wires are connected to the cathode cylinders so that any sharp points on them are sputtered off and they will be clean. Liquid air is put onto the trap, too, during this time to collect the mercury vapor. The tubes are then filled with hydrogen to the desired pressure. At first, we admitted the hydrogen through a palladium regulator so as to improve its purity, but later we found out that ordinary tank hydrogen serves very well. For small tubes, with cathode cylinders not over 15 mm diameter, 100 mm pressure of hydrogen has been found to be satisfactory. The whole process usually requires from four to twelve hours depending on the condition of the cathodes at the beginning.

Before the tubes are sealed off, their static characteristics are taken and the minimum point determined. If the minimum point is not sharp and definite and the minimum maintaining current not at least 3 microamperes, the gas is pumped out and the sputtering is resumed. In no case has a tube been found to behave unsatisfactorily in a counter circuit if it meets these requirements as to its minimum point. With these precautions the yield of good tubes is 100 percent.

Various combinations of cathode materials and gases were tried. The anode center wires were all of tungsten of 3 mil diameter. Al, Cu, Ni and W cathodes were tried with air, oxygen, argon, and hydrogen gases. The tubes were all made according to the same procedure. When air or oxygen was used, the electrodes never became bright but were coated with oxide. Of the electrode materials, all proved satisfactory except aluminum. Tubes with Al cathodes had too low an end-point and in many cases could produce no counts at all. When they did produce counts, many of these were spurious and so made such tubes unreliable. Our experience with aluminum seems to be in accord with that of a number of workers with whom we have discussed the matter, but others apparently are able to make satisfactory counters with aluminum cathodes.

We never succeeded in making a reliable counter with pure argon. None of them had any plateau and all produced many spurious counts. When the pulses were examined with a cathode-ray oscillograph at the input to the thyratron operating the Cenco recorder, trains of pulses of varying amplitude were frequently observed instead of sharp, clean, single pulses, such as indicate reliable counting. Oxygen and air were better than argon, and tubes filled with these gases sometimes had fairly definite plateaus. However, trains of pulses could often be observed with a cathode-ray oscillograph when these tubes were used, and the number of spurious counts was too high to be ignored in quantitative work. The minimum point of the static characteristic was often not very definite with air-filled counters. The discharge current would sometimes vary in an irregular manner at a voltage of 10 to 15 volts

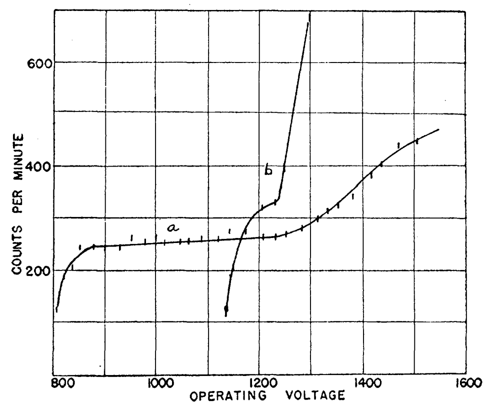

FIG. 2. Plateau curves for (*a*) hydrogen-filled and (*b*) air-filled counters. Copper cylinders, tungsten wire anodes.

above the minimum, though the discharge would not break. Tubes which exhibited these characteristics were invariably erratic in counting.

Hydrogen-filled tubes were far more reliable and regular in their behavior than any of the others that we tried. When the electrodes had been well cleaned by sputtering and the gas was pure, these tubes had very definite end points, the discharge breaking suddenly and sharply when the voltage was reduced to V_{min}. The pulses observed with a cathode-ray oscillograph were clean, single pulses and remarkably uniform in amplitude. Few spurious counts could be detected before the end of the plateau. Furthermore, the counting range always began at V_0 with hydrogen-filled tubes while the beginning of the counting range was sometimes considerably higher than V_0 for tubes filled with air or other gases. The hydrogen-filled tubes had much wider and more definite plateaus than any of the others, as has previously been reported by Cosyns and de Bruyn.[3] Fig. 2 shows plateau curves for two similar counter tubes, one filled with hydrogen and the other with air. As may be seen from the figure, the hydrogen tube has a plateau of about 400 volts. The vertical lines drawn through the observation points indicate the standard deviations for the number of counts taken to determine each point. Because of the obvious superiority of hydrogen-filled tubes we have come to use them exclusively, and the reliability tests described below were made with a hydrogen-filled tube.

The behavior of tubes filled with different gases has led us to postulate that one of the chief sources of spurious counts and erratic behavior in Geiger-Müller counter tubes and one cause for the ending of the plateau before the counting range, is in the action of metastable atoms. The reason for the failure to make successful tubes with pure argon is probably because argon has very prominent metastable states. Other gases with prominent metastable states as Ne, N_2, etc. have been shown to give narrow plateaus.[3] On the other hand, the reliability of hydrogen-filled tubes we ascribe mainly to hydrogen's lack of metastable states. Furthermore, it is the common practice of many workers with Geiger-Müller counters to add an admixture of oxygen or some other gas to argon if this gas is used as the filling gas. The improvement in the behavior may then be ascribed to the destruction of the metastable argon atoms by impacts of the second kind with the molecules of the admixed gas.

If the discharge mechanism described above is correct, one would expect spurious counts when a gas whose molecules have metastable states is used. Since metastable atoms are not propelled by an electric field, they will remain in the gas until destroyed by some impact of the second kind or by collision with an electrode or the tube wall. They may remain for a considerable time in a pure gas at high pressure. Any one of a number of different processes involving metastable atoms may result in the extraction of an electron from the cathode or in the ionization of a molecule of an impurity in the gas. An electron thus produced would have the same chance of starting a discharge and causing a count as an electron produced by the ionizing radiation being studied, and so spurious counts may occur at any time during the interval metastable atoms are present.

By an impact of the second kind, a metastable atom may ionize a gas molecule whose ionization potential is less than the potential of the metastable state. Or the metastable atom may excite the molecule with which it collides or be itself shifted to a radiating state. Light quanta thus produced may fall upon the cathode and cause the emission of a photoelectron and produce a count. If a metastable atom strikes the cathode,

[3] Cosyns and de Bruyn: Académie royale de Belgique, Bulletin de la Classe des Sciences [5] **20**, 371 (1934).

it may extract an electron therefrom and so cause a count. Consequently it seems best to use for Geiger-Müller counter tubes a gas like hydrogen which has no metastable states. We advocate doing this rather than putting in an admixture of some gas in sufficient amount to destroy metastable atoms so quickly that a short relaxation time is attained. The amount of the admixed gas necessary is enough so that its own excitation, direct and by second kind impacts, cannot be neglected in comparison with that of the main gas, and, if its molecules should have metastable states, they would not be quickly destroyed as their potentials would generally be lower and not in resonance with the excited states of the argon.

A rather extensive series of reliability tests was made on a Geiger-Müller counter apparatus consisting of a hydrogen-filled counter tube coupled to a thyratron single scale recorder by means of a Neher-Harper circuit. The tube had a 400 volt plateau, 850–1250 volts, and the operating voltage was set at about 100 volts above the threshold counting voltage. The tube was mounted on a paraffin block and surrounded by a brass frame into which small sources of radioactive material could be inserted in fixed positions. The tube and the sources could not easily be displaced with respect to each other. The sources were made by carefully dropping a drop of radium dial paint into a hole drilled into the end of a brass rod. A number of these sources were made in this way and numbered so that they could be identified. They were then inserted into numbered holes in the brass frame surrounding the counter tube and used singly or in combination. When a source was not in its place in the frame, a similar brass rod without any radioactive material was inserted in its stead so that there was always the same distribution of metal around the tube no matter how many of the sources were in use. Thus the scattering was always the same and an accurate multiple addition test could be carried out by calibrating the sources singly and using them in combination. Also other methods of calibrating the counters and circuits were devised and will be described in another paper.

TABLE I.

Counts	Counts per Min.	Stand. Deviations
9255	48.97	0.52
9595	49.97	.51
10935	49.48	.48
21757	50.13	.34
51542	49.75	.22
9616	54.02	.54
9832	53.15	.53
10210	52.63	.52
14599	52.89	.44
9688	53.82	.53
12984	54.10	.46
10665	52.28	.51
29222	52.00	.31
16664	52.08	.41
123480	52.79	.15
10181	58.85	.58
29857	58.09	.34
14956	56.23	.48
7140	59.01	.69
21784	59.68	.40
20329	58.92	.41
16830	57.03	.45
121077	58.24	.17
95096	130.45	.42
13708	131.81	1.11
21983	129.31	.89
9835	131.13	1.32
140622	130.45	.35

The apparatus designed for making addition tests was used for the reliability tests. A sufficient number of sources were inserted in the frame to give the desired average rate of counting, and then a considerable number of counts, from 7000 to 30,000, were taken and the average rate of counting was determined. This was repeated several times until the total number of counts at a given average rate reached 50,000 to 140,000. Tests were made at four different average rates of counting and the data are given in Table I and in Fig. 3. The tests extended over a period of three weeks during which time the apparatus was started and stopped many times. The zero or background count was taken at different times during this period and was found to be remarkably constant as is shown by the data in Table II. Six different observers participated in taking the data.

In Fig. 3, the horizontal lines for a given test are separated by twice the amount of the standard deviation for the total number of counts taken at one rate. The vertical lines through the points representing the individual observations are drawn of lengths indicating the standard deviations for the number of counts taken for that observation. It will be noted that more than half of these lines intersect with the horizontal lines and that the maximum deviation of an individual observation from the mean rate of counting is less than 2 counts per minute. Thus the deviations are within the expected limits for a random phenomenon like the one observed, and we conclude that the counting apparatus gave completely reliable quantitative data.

Counter tubes made according to the technique described above are photoelectrically sensitive to daylight and also to light from incandescent tungsten lamps. In using them it is best to shield them from such light, as the zero count is thus reduced and accidental variations in the intensity of the light are avoided. The tubes were shielded from light during the reliability tests but were not shielded from secondary cosmic radiation. When the tube was surrounded by two inches of lead, the zero count dropped from 12 to about 2 counts per minute. The remaining counts were probably due to primary cosmic rays. The cylindrical cathode for this counter was a copper gauze cylinder 7 mm in diameter and 40 mm long.

TABLE II. *Background due to primary and secondary cosmic rays.*

Date	Counts	Counts per Min.
Mar. 23	6143	12.80
" 24	4094	12.41
" 25	4857	12.78
" 25	3958	12.81
" 31	6628	12.25
Apr. 1	3894	11.84
" 16	17840	12.52
Total	47414	12.50

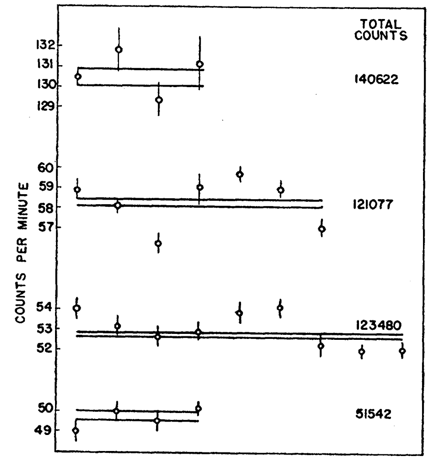

FIG. 3. Reliability tests on a single scale Geiger-Müller counter apparatus.

There is nothing in the tests described to indicate what might be the absolute efficiency of the counter. Such tests are important and are often made by research workers on cosmic rays by inserting an additional tube in a bank of coincidence counters and observing the decrease in the counting rate which follows. It might be pointed out in this connection that one may make a mistake in trying to make counter tubes with considerable volume and a low zero count. Unless the tube is well shielded with lead, secondary cosmic rays are invariably present and a too low zero count then indicates that the counter tube is insensitive and has a low absolute efficiency.

We wish to acknowledge with thanks financial aid from the Horace H. Rackham Foundation which made it possible to undertake this research.