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The requirements of high gain and low background current in an electron-multiplier tube for the direct detection of high energy particles are considered. The design and construction of an experimental electron-multiplier tube with a stable over-all gain of at least $10^8$ and a background at room temperature corresponding to three or four electrons per minute released at the input is described. An 0.0008-inch thick nickel window is provided in the tube envelope to admit the high energy particles to the multiplier. The efficiency of this device is compared quantitatively with that of a Geiger tube as a detector of beta-particles. It is found that the over-all beta-particle counting efficiency of the tube is of the order of 1.3 percent, and that the efficiency of the oxidized silver magnesium target surface is 4.9 percent for a uranium source and 6.0 percent for a strontium source.

I. INTRODUCTION

The main purpose of this investigation was to determine the feasibility of using a high gain secondary-emission electron-multiplier tube directly as a detector of high energy particles, particularly beta-particles, and to determine quantitatively the efficiency of its operation.

The use of electron multiplier tubes as detectors of high energy particles has been reported in the literature, but only in a rather qualitative form. Z. Bay\(^1\)\(^2\) has described briefly the use of the electron multiplier tube in counting photons and gamma-rays, and he has described in more detail\(^3\) the application to alpha-, beta-, and x-rays. Bay reports\(^4\) that he was able to count every alpha-particle and "perhaps" every beta-particle. The efficiency of counting gamma- and x-rays was about that obtainable with an ordinary Geiger-Müller counter.

J. S. Allen\(^5\) has applied the electron multiplier to the mass spectograph for counting of positive ions and electrons. He also reports\(^6\) using a multiplier tube as an alpha-particle detector with near 100 percent efficiency. More recently, Allen has described\(^7\) an electron-multiplier particle counter applied to an electron spectrometer and as an alpha-particle detector.

In an effort to minimize unwanted currents in their high voltage apparatus, Trump and van de Graaff\(^8\) have made an experimental study of the secondary-emission ratio of several metals with primary electron velocities in the range of 30 to 340 kilovolts. Their data seem to indicate that the secondary-emission ratio is roughly inversely proportional to voltage in this region, being 0.12 for tungsten and 0.05 for aluminum at 300 kilovolts. The secondary-emission ratio is here defined as the ratio of the number of low velocity secondary electrons to the number of incident primary electrons.

From an extrapolation of Trump's data into the megavolt region it might be guessed that a secondary-emission beta-particle detector would have only a few percent efficiency, due to the small probability that an incident beta-particle would release a low velocity secondary electron. In a recent survey article on counting techniques Corson and Wilson\(^9\) state: "With beta-particles the average number of secondaries per incident particle is small—The result is a low counting efficiency for beta-particles, although quantitative data are not available." These quantitative data were sought in this investigation.

II. REQUIREMENTS OF THE MULTIPLIER TUBE

It is necessary for satisfactory detection of high energy particles that the electron-multiplier tube have sufficiently high gain and sufficiently low background noise that the incidence of a single electron at the input can be detected.

Assuming a secondary-emission ratio of greater than unity, the gain may be made as large as desired by using a sufficient number of stages. With a twelve-stage multiplier a stable gain of at least $10^8$ was readily obtained.

The factor limiting the amount of gain which may be employed is the noise or "dark current" of the multiplier. Rajchman\(^10\) has made a careful analysis of the sources of dark current in electrostatic electron multipliers. He lists the following as the main causes of dark current:

1. Ohmic leakage to the collector circuit,
2. The effects of ionization of the residual gas,
3. Ionization of gas molecules by electron impact,
4. Ionization by secondary electrons from the cathode or anode,
5. Ionization by electric fields.

\(^1\) Z. Bay, Nature 141, 284 (1938).
\(^2\) Z. Bay, Nature 141, 1011 (1938).
\(^3\) Z. Bay, Rev. Sci. Inst. 12, 127 (1941).
\(^5\) J. S. Allen, PB49548, U. S. AEC.
\(^7\) J. G. Trump and R. J. van de Graaff, Phys. Rev. 75, 44 (1949).
\(^8\) D. R. Corson and R. R. Wilson, Rev. Sci. Inst. 19, 207 (1948).
(3) field emission from the conductors within the tube,
(4) thermionic emission of the electrodes.

The collector system must be appropriately designed, in both the internal tube structure and the external circuit, so as to minimize ohmic leakage. If present, this leakage may cause not only a varying d.c. component of the background current but also spurious pulses due to rapid fluctuations.

If there exists physically within the tube a direct path from output to input it may be possible to maintain a continuous current flow within the tube with no external excitation, due to ion feedback. The residual gas may be ionized by the electrons as they follow their normal paths through the multiplier. The positive ions so formed will tend to travel backwards in the multiplier structure from output toward input, releasing secondary electrons at the input if they strike the target surface. They thus constitute a positive feed-back link, which could be triggered by any residual electrons in the multiplier. Therefore, the tube design should be such as to best isolate the output from the input.

Field emission will occur at the surface of a conductor when the potential gradient is sufficiently large. It is thus necessary to physically design the multiplier structure to minimize the potential gradients, and to eliminate any sharp edges or projections from the parts at points of high gradient.

The foregoing causes of dark current may be reduced to a negligibly small value by exercising sufficient care in design and construction of the multiplier tube. The thermionic emission of the tube electrodes is, however, a fundamental limitation. This follows the standard Richardson equation for temperature-limited thermionic emission, with the temperature of the emitter being approximately room temperature. If the number of electrons released at room temperature is to be no greater than ten per minute, the work function of the emitting surface must be greater than 1.0 to 1.5 volts. For many of the commercially used secondary-emission surfaces the work function is considerably less than one volt. Thus the material for the secondary-emission surfaces must be selected with care.

If one must use a material of low work function for the secondary-emission elements, it is possible to reduce the thermionic emission by cooling of the multiplier structure. In a 931-A multiplier photo-tube, R. W. Engstrom found that the room temperature thermionic emission from the first stage was of the order of \(10^{-14}\) ampere. This is equivalent to about \(10^6\) electrons per minute. By cooling the tube to liquid air temperature the background count was reduced to about ten per minute.

While cooling of the multiplier tube may be practical in some cases, there may be experimental arrangements in which this would not be possible. Thus the use of a secondary-emitter material with a high work function is the more desirable solution to the problem.

III. DESIGN OF THE MULTIPLIER TUBE

Aside from the consideration of the general requirements of a high gain multiplier tube and the mechanical problems involved in its actual assembly, the main design problem is one of determining suitable electron optics. There are two general methods of accomplishing the proper focusing of electrons from stage to stage: by the use of either magnetic or electrostatic fields. In either case the electrons follow the paths indicated by simple ballistics.

In designing an electrostatic multiplier structure it is most useful, if not essential, to be able to predict the electrostatic field due to a given configuration of electrodes and the motion of an electron in this field. There are several quite useful experimental methods of determining electrostatic fields and electron trajectories. These are described in some detail by Zworykin and Rajchman in their article on the development of the electrostatic electron multiplier.

The rubber model is a convenient experimental method which solves simultaneously the potential distribution and trajectory problems. Elevation on a suitably stretched rubber membrane corresponds to the potential field within the tube, and the trajectories of small balls are similar to the electron paths.

The rubber model technique was used in the development of the electrode structure for the multiplier tube used in these experiments. For the main multiplier chain it was decided to use a design known as the L16 element which had previously been developed by Rajchman for high gain, low dark current applications.

In the design of the input system it is desired that a target as large as possible be exposed to the incident radiation, and that all secondary electrons originating at this target be focused into the multiplier chain. It is also necessary in the design of the input system to take into account the thin window in the vacuum envelope which admits the high energy particles into the multiplier. It is desired that any low velocity electrons which might be released at the inner surface of the thin window would also be directed into the multiplier chain. Thus each incident particle would have two opportunities to be detected, one by the release of secondary electrons as it passed through the window and another as it struck the target. The structure developed presents a useful target area of 0.8 square inch.

In the design of the collector electrode, it is desired to collect all the electrons from the last multiplier element, and not to disturb too badly the electron trajectories between the next-to-last and the last elements. Also, the collector should physically close the end of the multiplier chain, to minimize the possibility of ion feedback. Since the signal currents involved in this application are quite small it is not necessary to consider the effect of changing collector potential due to the ohmic drop caused by the signal current flowing in the load resistor. If this were not negligibly small, a much more complex collector system would be required to obtain a pentode characteristic.

The outline of the complete tube structure is shown in Fig. 1, together with the approximate electron paths. While the tube was designed for ready fabrication, it should be emphasized that it is entirely of an experimental nature and not available commercially.
precaution in order to secure reproducible results with the secondary emission surfaces. Kovar was chosen as the base metal for the seal flanges because of the necessity of matching the thermal expansion of the adjacent glass section of the stem. It is possible to copper plate the Kovar and make the usual gold-to-copper diffusion seal to the copper plating.\textsuperscript{12} In the final assembly of a tube, massive clamps are arranged to squeeze a ring of gold wire between the copper plated Kovar sections. The clamps contain a large copper section whose expansion on heating will increase the pressure on the gold ring. The actual diffusion of the gold into the copper is effected as the tube is baked out on the exhaust pumps.

A copper pinch-off tubulation was chosen to eliminate the possibility of contamination from gas released in the usual glass tip-off. In effecting the pinch-off, the copper tubulation is simply squeezed under great pressure until it is pinched in two. If the surfaces are clean, a vacuum tight seal invariably results.

After the main features of the design had been worked out as outlined above, there still remained the problem of mounting a suitable thin window in the wall of the tube envelope for the admission of the beta-particles.

The requirements on this window are twofold: that it be such that the high energy beta-particles may readily pass through it, and yet sufficiently strong mechanically to form part of the vacuum envelope of the tube.

The first requirement implies that the product of thickness times density be a minimum for the material used for the window. The second requirement implies that this thin foil be sufficiently strong mechanically to withstand evacuation, and rugged enough to form a reliable portion of the tube envelope. It is also necessary that the thin foil be capable of being suitably sealed to the envelope assembly, and moreover that it be capable of withstanding a bake of 450°C while evacuated.

For similar applications in Geiger tubes windows of thin mica or aluminum are used. They are usually clamped or waxed in place. Neither of these techniques would be satisfactory for the present tube. Grade A nickel was available in sheets 0.0008 inch thick. Disks of this material are readily silver soldered into the cupronickel cups in a hydrogen furnace. The windows so formed withstand evacuation and baking without oxidation and have shown no tendency to leak or rupture. The unsupported area of this window is \( \frac{1}{4} \) inch in diameter.

Thus from the mechanical standpoint the nickel windows seem to be entirely satisfactory; they are quite easily fabricated and require no special techniques in handling. From the standpoint of transmission of beta-particles, the nickel should be slightly inferior to the aluminum. The thickness-density product for the 0.0008-inch thick nickel window is 0.0178 grams per square centimeter. This should just pass 130 kv beta-particles. This is a sufficiently low value for the tests contemplated. Therefore, because of their satisfactory mechanical properties the 0.0008-inch thick nickel windows were used on the tubes intended as beta-particle counters.

\textbf{V. TESTS ON THE MULTIPLIER TUBES}

The first two tubes constructed had substituted in place of the thin window a header containing leads which supported several small tungsten filaments just inside the envelope. By heating these filaments it was possible to introduce electrons into the structure as if they were originating at the back of the window. By this means it was possible to study the behavior of the multiplier and to measure its over-all gain. This is plotted in Fig. 4, together with the d.c. background current. This d.c. background was determined to be largely ohmic leakage to the collector system.

From the test data it was determined that the secondary emission ratio was quite constant from stage to stage in the multiplier. The variation with voltage of the secondary emission ratio of the oxidized silver magnesium surfaces is plotted in Fig. 5.

Having thus determined the d.c. characteristics of

\textsuperscript{12} Law, Whalley, and Stone, RCA Review 9, 643 (1948).

![Fig. 4. Variation of over-all gain and d.c. background with voltage.](image-url)
the multiplier, the possibility of detecting single electrons as its input was next investigated. The total charge deposited on the collector by a pulse originating as a single electron at the input will be the charge on the electron times the gain of the multiplier. The voltage pulse developed at the collector will be the quotient of this total charge divided by the capacity of the collector system. In order to avoid adding any cable capacity to the output capacity, a cathode follower stage was connected directly to the load resistor and all further observations made at the output of the cathode follower.

With the cathode follower in place the measured total output capacitance of the multiplier was $15.5 \times 10^{-12}$ farad. Thus with a multiplier gain of $10^7$ a single electron should produce about a 0.1-volt pulse at the output. This could be readily observed with an ordinary laboratory oscilloscope containing an amplifier.

When the system was set up under these conditions and the filaments at the input heated slightly, a random "rain" of pulses of about the expected amplitude was observed on the oscilloscope. When the heating current was removed from the filaments it was found that there was still a scattering of pulses due to photoelectric emission caused by light entering the glass portions of the envelope. As these glass portions were progressively shielded the number of pulses decreased until with the structure in total darkness the background rate was 3 or 4 pulses per minute.

From the preceding tests it was concluded that the sensitivity of the multiplier was adequate to detect single electrons at its input, and that the number of background pulses was sufficiently low to permit room temperature operation.

In all, three tubes were assembled using the 0.0008-inch thick nickel window for the tests of efficiency of counting beta-particles.

The radioactive sources available were a small piece of uranium metal and a sample of strontium 90. Both of these are beta-emitters which are relatively free of other forms of radiation. The uranium source has a spectrum made up of several components with a maximum energy of 2.3 Mev. The spectrum of the strontium has a maximum at 0.3 Mev and a high energy cut-off of 2.4 Mev. The incident intensity of the sources was checked by observing the response of a thin mica window Geiger tube when given the same exposure as the window of the multiplier tube.

When the sources were placed before the window of the multiplier tubes pulses were observed at a rate considerably above the background pulse rate. These were analyzed with the aid of a pulse height discriminator and recorder. As the cut-off bias on the discriminator circuit was lowered, more and more pulses would have sufficient amplitude to be recorded within a given period of time. Thus a distribution curve of pulse height versus the number of pulses having this or greater height may be obtained.

![Graph showing variation of secondary emission ratio versus voltage.](image)

The data were taken under two different conditions of test. The first was the normal connection in which low velocity electrons could be focused from both window and target. In the second the window was biased positive with respect to the target, so that no low velocity electrons would be focused from window to target. In this second condition the contribution from the target surface alone can be analyzed. Representative distribution curves are shown in Fig. 6.

From data of this sort the beta-counting efficiency may be readily determined. From the data one must assign some numerical value for the total number of counts observed for each curve. The number arbitrarily assigned to each curve is its intercept with the zero pulse height axis. This choice assumes that the observed distributions may be extrapolated to zero amplitude, and counts all pulses of greater than zero amplitude.

The over-all efficiency of the tube with the normal connection is defined as the ratio of the number of counts recorded by the multiplier tube to the number of beta-particles entering the window, the source being at a distance of 0.5 inch from the window. This over-all efficiency of the multiplier tube with the normal connection is:

<table>
<thead>
<tr>
<th>Tube</th>
<th>Strontium source</th>
<th>Uranium source</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 3</td>
<td>1.1 percent</td>
<td>1.6 percent</td>
</tr>
<tr>
<td>No. 5</td>
<td>1.1 percent</td>
<td>1.5 percent</td>
</tr>
</tbody>
</table>

For the window-biased-off condition, the efficiency of the oxidized silver magnesium target surface is defined as the ratio of the number of counts observed with the multiplier to the number of beta-particles striking the active area of the target, the source being 0.5 inch in front of the window. This target efficiency is calculated to be:

<table>
<thead>
<tr>
<th>Tube</th>
<th>Strontium source</th>
<th>Uranium source</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 3</td>
<td>6.1 percent</td>
<td>4.7 percent</td>
</tr>
<tr>
<td>No. 5</td>
<td>5.9 percent</td>
<td>5.1 percent</td>
</tr>
</tbody>
</table>
The target efficiency tabulated above is perhaps the more significant since it is a property of the target material itself, while the over-all efficiency is affected by scattering and solid angle dispersion between the window and target, and is thus a function of the particular geometry used.

The third thin window tube suffered a mechanical mishap during assembly and while its tests tended to confirm the results obtained with the other tubes they could not be placed on the same quantitative basis, and were thus omitted from the tabulation above.

Tests were then made with essentially uniform excitation of all the stages of the multiplier. One of the early tubes had a glass section in its envelope. This was strongly illuminated, and the light was scattered throughout the interior of the tube by its bright internal parts. Pulse height distribution measurements were then made of the photoelectric pulses thus produced by the uniform excitation of all stages. The curve was the same shape as that for the radioactive samples for pulses of greater amplitude than the average pulse height. For decreasing pulse amplitudes, the curve rose rapidly as the contributions of successive stages of the multiplier became evident.

This is similar in form to the curves observed with radioactive excitation, although in this latter case the rise is not as steep as would be expected for uniform excitation of all stages. This suggests that in the radioactive case the main contribution is coming from the target (with the window-biased-off connection) but that there is some scattering of the primary particles to the following stages. That this scattering exists was verified by setting up the input system in air and measuring the intensity of scattered particles at the position of the multiplier stages by means of a Geiger tube. By this measurement it is estimated that 20 percent as many particles may strike the following stages of the multiplier as strike the target.

For the tubes under study it is difficult to arrive at a definite quantitative estimate of the detailed form of the target distribution curve from the observed window-biased-off curves. The factors involved are the proportion of the incident particles which strike the active region of each of the successive multiplier stages, and the efficiency of release of low velocity secondaries at each of these surfaces. However, the form of the observed distribution curves is now understandable. Because of this effect it is estimated that the true target efficiency may be as much as 20 percent below that indicated by the calculations based on the linear extrapolation. By the same reasoning the over-all efficiency of the multiplier may be as much as 10

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Fig. 6. Representative distribution curves for radioactive source.

The results with the various tubes are thus in good agreement, and moreover the secondary emission gain was quite uniform in all the tubes constructed.

VI. FURTHER TESTS AND CALCULATIONS

In all the pulse height distribution data at hand it appeared that the experimentally observed points could be reasonably well fitted by a straight line on the semilogarithmic plots presented. This would indicate an exponential pulse height distribution curve. This is not the form of distribution curve expected from an electron multiplier, which should show a leveling off at low pulse amplitudes.\[13\] Tests were then carried out to examine more carefully the shape of the observed distribution curves, and to determine why they were not of the expected shape.

First, the gain of the pulse amplifiers ahead of the pulse height discriminator was increased so that the fixed range of the discriminator was effectively shifted into the region of smaller pulse amplitude. The distribution curves obtained in this manner for the low amplitude pulses fitted smoothly onto the curves already presented, but instead of indicating any leveling off at low pulse amplitudes, showed that the observed curves actually rose a bit more steeply than an exponential at low pulse amplitudes.

Pulse height distribution measurements were then made on one of the early tubes with tungsten filaments at the head end, using the thermionic electrons as the input to the multiplier. It was then reasonably certain that the input thermionic electrons were striking only the target electrode, and that the observed output pulses were all originating at the target electrode. The pulse height distribution curve then showed the leveling off for low amplitude pulses, as would be expected for excitation confined to a single stage.

Tests were then made with essentially uniform excitation of all the stages of the multiplier. The target efficiency tabulated above is perhaps the most significant since it is a property of the target material itself, while the over-all efficiency is affected by scattering and solid angle dispersion between the window and target, and is thus a function of the particular geometry used.

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This is similar in form to the curves observed with radioactive excitation, although in this latter case the rise is not as steep as would be expected for uniform excitation of all stages. This suggests that in the radioactive case the main contribution is coming from the target (with the window-biased-off connection) but that there is some scattering of the primary particles to the following stages. That this scattering exists was verified by setting up the input system in air and measuring the intensity of scattered particles at the position of the multiplier stages by means of a Geiger tube. By this measurement it is estimated that 20 percent as many particles may strike the following stages of the multiplier as strike the target.

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percent higher than the value indicated by the linear extrapolation.

From the foregoing analysis it seems reasonable to assume that the linear extrapolation to zero amplitude of the observed data for the window-biased-off condition will indicate approximately the total number of low energy electrons which come off the target surface. It should be possible to verify this number if the nature of the energy distribution of the radioactive source is known and if the variation of secondary emission ratio of the target with incident energy is known.

From data recently published by Meyerhof\textsuperscript{14} the distribution of relative number of particles per increment of energy for the strontium source may be determined. The area under this curve is proportional to the total number of particles emitted from the source in a given time. Knowing the total number of counts observed with a Geiger tube, a scale of number of counts per unit increment of energy may be assigned. Thus, with this correlation, the number of incident particles per unit time at any given energy may be determined.

On a more detailed analysis of Trump's\textsuperscript{7} data on the ratio of low energy secondary electrons to high energy primaries it was found that this secondary emission ratio appeared to be roughly inversely proportional to primary voltage in the high energy region. Also from Trump's data it was observed that a smooth curve was obtained on plotting the secondary emission ratio due to high energy primaries (at say 300 kv) against atomic number, the ratio increasing with increasing number. In this manner the secondary emission ratio at 300 kv was estimated to be 0.04 for magnesium and 0.09 for silver, and their variation with primary energy was assumed to be similar to that of the other materials measured by Trump.

Since these secondary emission ratios are less than unity, they may be interpreted as the probability that a primary particle will release a low energy secondary electron. Curves were thus deduced for the variation with energy of the number of primary particles, and of the variation with energy of the probability of releasing a secondary. If the product of number of primary particles times the probability of release of a secondary is summed point by point throughout the energy spectrum, the total number of counts expected per unit time would be determined.

By this method it was computed that, if the target were all silver, 1600 counts should be observed in the 100 second interval, when the multiplier tube was exposed to the strontium source in the window-biased-off condition. If the target were all magnesium about 750 counts would be expected under like conditions. The target is a mixture of silver and magnesium, and while the exact mechanism of release of secondary electrons is not known, it is at least certain that the primary particles must penetrate into the bulk of the material.

Thus the observed number of counts, 1000, is between the computed extremes, and is thought to be a reasonable correlation. This indicates that the present determination of secondary emission ratio due to beta-particle excitation is in agreement with the data obtained by Trump on the secondary emission ratio with excitation by thermionic electrons accelerated by a van de Graaff generator.

VII. CONCLUSIONS

One of the initial objectives was the design and construction of an electron multiplier tube with sufficient over-all gain and sufficiently low background current so that single electrons released at its input might be detected. Having such a structure it was desired to mount a suitable thin window in its envelope to admit the beta-particles so that a sealed-off vacuum tube could be constructed. It may be said that all of these requirements were satisfactorily met by the tubes constructed.

Having this tool available, it was desired to determine quantitatively the efficiency of the electron multiplier in directly counting beta-particles. The results obtained from tests on three tubes with two different beta-particle sources are in good agreement. It is indicated that the over-all beta-particle counting efficiency of the electron multiplier tube is of the order of 1.3 percent. The efficiency of the oxidized silver magnesium target surface appears to be 6.0 percent for the strontium source and 4.9 percent for the uranium source. It is to be expected that the efficiency be higher for the strontium since it has stronger low energy components, and the secondary emission ratio is decreasing for increasing energy. The over-all efficiency is lower than the target efficiency because of solid angle dispersion and scattering within the tube between the window and the target. The target efficiency is a basic property of the material while the over-all efficiency is a characteristic of the particular tube structure employed.

This tube should be useful in applications where its low efficiency is not disadvantageous, such as high level monitoring. It should be particularly useful in monitoring high intensity radiation because it does not “block” at very high counting rates, but gives a steady output current whose magnitude is proportional to the intensity of radiation. This tube should also be useful where a very low background count is essential. In a demountable system, the multiplier structure could be inserted directly into the vacuum chamber without the intervening window and measurements made of all particles with energy of a few hundred volts or greater.

In conclusion, it is a pleasure to acknowledge the advice and helpful criticism from Professor C. H. Willis and the late Professor H. C. Rentschler of the Department of Electrical Engineering, Princeton University and from Drs. I. Wolff, E. G. Linder, and C. W. Mueller of the RCA Laboratories staff.

\textsuperscript{14}W. E. Meyerhof, Phys. Rev. 74, 621 (1948).