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New Devices and Methods of Measurement

ELECTRON MULTIPLIERS OF THE OPEN TYPE

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I. INTRODUCTION

AT the present time secondary-electron multipliers of the open type or, as they are also called, windowless multipliers, are rather widely used for detection of electromagnetic radiation in the spectral region 1—1500 Å,[1-7] electrons with energies up to several tens of keV, and also ions and neutral particles of low and medium energies (up to several thousand keV.[8-15] These detectors consist of an electron-optical system with secondary-emission amplification of the electron current produced by the radiation at the cathode of the device, similar to those used in ordinary photoelectron multipliers. However, in contrast to the latter, these systems do not have the usual protective vacuum envelope, and this is responsible for three features of the open-type multiplier:

1. Absence of a protective enclosure, and consequently also the possibility of removal of any window separating the source of radiation and the cathode (usually the first dynode of the multiplier), results in a substantial gain in efficiency and broadening of the spectrum recorded (range of energy of the particles) by avoiding absorption in the windows, which is extremely important for the types of radiation mentioned above. Thus, while transmission of even so slightly absorbing a film as celluloid only 1000 Å thick amounts to 84% for radiation with a wavelength of 44 Å, the transmission drops to 4% at λ = 308 Å.[2] Therefore, such well known detectors as ionization chambers and gas counters with mechanically durable windows of mica, beryllium, and aluminum have some sensitivity only in a limited region of wavelengths—in the short-wavelength part of the spectral region 1—1500 Å or in regions adjacent to absorption edges in the window material.[16] The region of efficiency of the counters can be extended if nitrocellulose windows several hundred angstroms thick are used.[17] However, since these films are very weak and it is difficult to make them vacuum tight, counters with these windows must be used with a continual replenishment of the gas mixture[17] and with simultaneous admission of air into the apparatus and into the counter. This considerably complicates work with the counter and is not always possible.

The appreciable absorption of electrons and photons in the films protecting scintillator crystals, the low energy of the radiations in question, and also the rapid destruction of the crystals by ions do not permit efficient detection of these radiations by scintillation counters.[18,84]

In contrast to the detectors described, in an open multiplier the variation of efficiency with λ or particle energy is determined only by the characteristics of the cathode. The value of these detectors lies also in their simplicity, the high time resolution characteristic of multipliers, the low intrinsic background (0.1 electrons per second) and the possibility of recording currents as low as 10^{-20} A,[19] and also, with an appropriate choice of cathode, the possibility of building solar-blind and other selective detectors,[20,21] i.e., detectors capable of recording short-wavelength radiation in a background of intense radiation in the visible spectrum. In addition, investigations in recent years have shown that open multipliers can be used to make absolute measurements of the intensity of the detected radiation. The advantages of open multipliers are particularly obvious in research in space, where the multiplier works under conditions of a natural vacuum.[22-24]

The possibilities enumerated have naturally produced great interest in these detectors, as indicated by the considerable number of papers published both in the U.S.S.R. and abroad.[8,12,13,25-43] This interest has not diminished even after the development of cathodoluminescence detectors,[44,45,84] which also have no entrance window. In the latter, a flux of electrons from the cathode (of a material similar to that used in multipliers) is accelerated and produces light flashes in a scintillator, which are recorded by a photomultiplier. Because of the substantial intrinsic background of photomultipliers and their high sensitivity to scattered radiation, these detectors are usually used to detect rather intense radiation fluxes.[46] Therefore the open multiplier remains at the present time the most sensitive device capable of recording currents from the cathode of an instrument, beginning at 10^{-19}—10^{-20} A.

2. Because there is no protective enclosure, it becomes necessary to preserve unchanged the parameters of the multiplier on contact of the emitting surfaces with air, which is unavoidable in operation of multipliers in demountable vacuum equipment. Ordinary photomultipliers do not have this stability. Interaction with air leads also to formation of a layer, however thin, of oxide dielectric on the emitting surfaces which makes it difficult to assure stability of the multiplier parameters during extended operation, i.e., during extended bombardment of the emitting surfaces by the electron flux produced in the multiplier, and also imposes a limitation on the achievable output current. In choosing a means of overcoming these difficulties, it is necessary to keep in mind that the emitting surfaces of an open multiplier should have, in addition to stability of characteristics, an adequate secondary-emission coefficient σ to achieve a high gain K in the secondary-emission multiplier and a high photoelectric work function in order to assure low intrinsic background and the possibility of detecting short-wavelength radiation in the presence of radiation in the visible portion of the spectrum. Therefore the problem of constructing a

multiplier of the open type consists first of all in choosing special materials for the emitting layers both of the dynodes and of the cathode, and methods of preserving their characteristics.

3. It is necessary to have a detector design which will provide adequate stability and the possibility of rapid replacement or removal from the equipment during adjustment. Because of the large number of problems arising in preparation and use of open-multiplier detectors and the existence of a very large number of publications on the subject, the present review can make no pretense of completeness. Its purpose is to acquaint the reader with certain designs of detectors, with the features of operation of open-type multipliers, with the materials used for dynodes and cathodes, with working hypotheses regarding the processes occurring on interaction of the emitting surfaces with air and with the electron beam, and with the characteristics of the multipliers and estimation of the accuracy of the measurements, i.e., with those questions which comprise a realistic approach to evaluation of the usefulness of open-multiplier radiation detectors and their field of application.

II. DESIGN AND PRINCIPLES OF OPERATION OF OPEN-TYPE MULTIPLIERS

1. Electron-optical Schemes and the Design of Multipliers

At the present time, open multipliers use practically all known multiplying systems, both with discrete dynodes and with continuous emitters. The electron-optical properties of these systems are described in a number of books[47] and reviews.[48]

Of the systems of the first type, the most often used are various modifications of the simple system with electrostatic focusing and trough-shaped dynodes,[9,28,30,31,42,43] which was first used for open detectors by Allen.[8] In detection of rather narrow beams of radiation, the function of cathode is served by the first dynode of the system (Fig. 1), which is covered by a material with the necessary spectral characteristics or with the necessary value of secondary-emission coefficient. Sometimes the first dynode is replaced by a flat plate placed at an angle to the radiation being detected.[1,9] For detection of rather wide beams, special input systems have been developed[27,42,48] (Fig. 2) with large-area cathodes which act as reflectors. The cathodes can be made replaceable,[42] which is convenient in detection of ion beams which destroy the cathode and particularly in detection of radioactive isotopes. The semitransparent cathodes usually used in photomultipliers cannot be used here

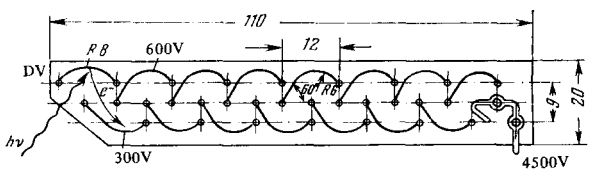

FIG. 1. One of the types of secondary-emission multipliers with trough-shaped dynodes.

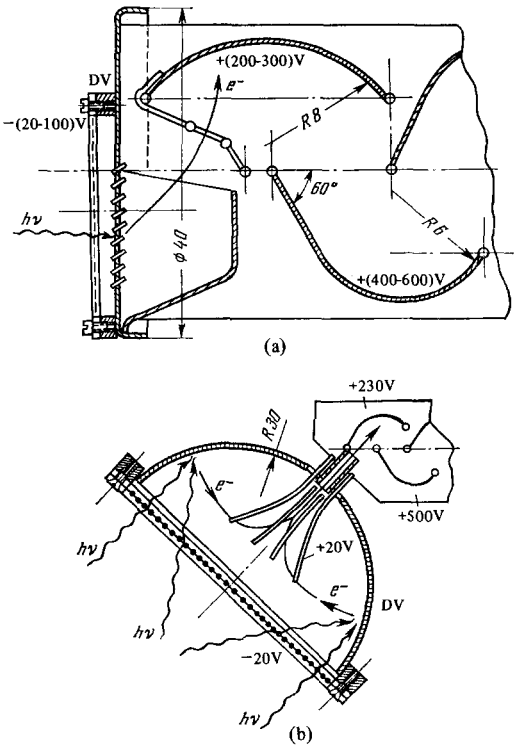

FIG. 2. Examples of multiplier entrance systems. a) Jalousie type cathode [42]; b) cathode in the form of a hemisphere. [48]

because of the absorption of radiation in them. In a number of applications[23] it is required to provide a constant output signal as the angle between the beam of radiation and the detector axis changes over a certain range. In this case cathodes in the form of a hemisphere (see Fig. 2) are useful, and also those in the form of a portion of a cylinder[54] (see Fig. 1). In multipliers with trough-shaped dynodes the optical coupling between the collector and the cathode is minimal, and the distances between the dynodes are rather large. This provides a low background level and permits achievement of a substantial gain per stage at the expense of increasing the potential difference applied to the multiplier. However, the focusing properties of the system do not permit the number of dynodes to be increased efficiently beyond sixteen. Therefore, in order to achieve high gain it is necessary to use dynode materials with a substantial secondary-emission coefficient which is stable against the action of air. The number of these materials is limited (see Chapter III).

As in photomultipliers, the dynode system can be assembled on mica mounting plates (Fig. 3a). In this design, the nickel feet of the dynodes can be connected by screw clamps to a voltage divider mounted in the vacuum of the research apparatus.[31] This construction rather quickly becomes loose if the multiplier is frequently removed. Better mechanical stability is obtained with multipliers assembled, for example, on ceramic mounting plates (Fig. 3b), on one of which are mounted the tabs for connection with the voltage divider.[42] Charging of the mica or ceramic supporting plates by the electron flux adversely affects the stabil-

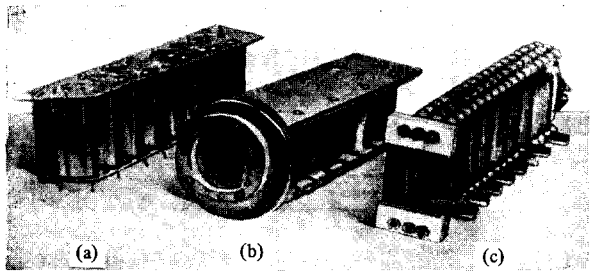

FIG. 3. External appearance of multipliers with trough-shaped dynodes. a) Multiplier mounted on mica [31]; b) multiplier with jalousie type cathode [42] mounted on ceramic plates; c) multiplier mounted on longitudinal posts. [43]

ity of the multiplier (see Chapter IV). This effect is avoided if the multiplier dynodes are mounted on longitudinal posts and have end caps[43] (Fig. 3c). Removal of dielectric materials from the path of the electron beam and increasing of the cathode area can also be accomplished by use of toroidal electrodes,[26] which have a cross section similar to that shown in Fig. 1. However, preparation of the toroids and assembly of such a system are rather complicated.

In addition to multiplier systems with trough-shaped dynodes, systems are also used with dynodes of the jalousie or Venetian-blind type,[29] similar to the FÉU-13, and with dynodes in the shape of a quadrant of a cylinder.[48] The jalousie type has adequate cathode and dynode area, is compact, can have a built-in voltage divider, and is not very sensitive to external electric and magnetic fields; in it the electron flux does not encounter the supporting structure, and the number of dynodes can be made as high as twenty or somewhat larger. However, dynodes of this type are deformed during the high-temperature processing which is necessary to assure high, stable values of σ (see Chapter III), and the small distance between the dynodes limits the potential difference applied between stages. The last remark refers also to the extremely convenient system with dynodes in the shape of a quadrant of a cylinder.[48] Therefore, with these systems it is usually not possible to obtain as high gain per stage as with trough-shaped dynodes.

By using crossed electric and magnetic fields,[25] it is possible to improve the focusing properties of multiplier systems with discrete dynodes, to increase the number of dynodes, and accordingly to make the dynodes of materials with low, stable values of σ. This system may make use of magnetic fields which already exist in the apparatus[25,33] and, because the electron trajectories are identified in this case, the system should have improved time resolution.[25] However, this type of multiplier is rather complex and unwieldy. Recently, as the result of development of techniques for obtaining stable semiconducting layers, focusing of electrons in crossed fields has been accomplished in extremely compact and simple multipliers with complex emitters[32-34,39] (Fig. 4a). The multiplier, shown in Fig. 5, consists of two glass or quartz plates on which are deposited layers which serve the purpose both of emitters and voltage divider, and a system of permanent magnets. The initial portion of the longer

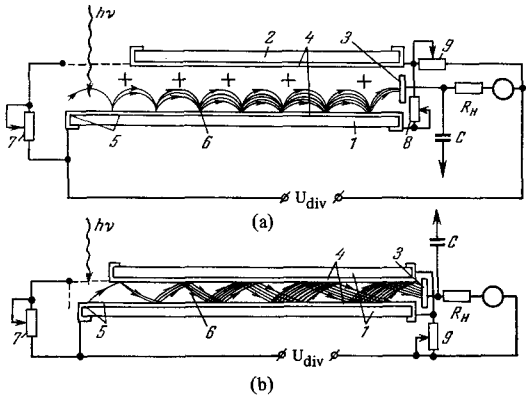

FIG. 4. Principle of operation of multipliers with extended emitters. a) multiplier with focusing in crossed fields (crosses--direction of magnetic field vector); b) slot-type multiplier. 1—Working (emitting) plate; 2—auxiliary (field) plate; 3—collector; 4--emitting and current-carrying layers (divider); 5—cathode region; 6—electron trajectory; 7, 8—potentiometers for compensation of difference in length of the plates and producing the field between the plates; 9—corrector potentiometer.

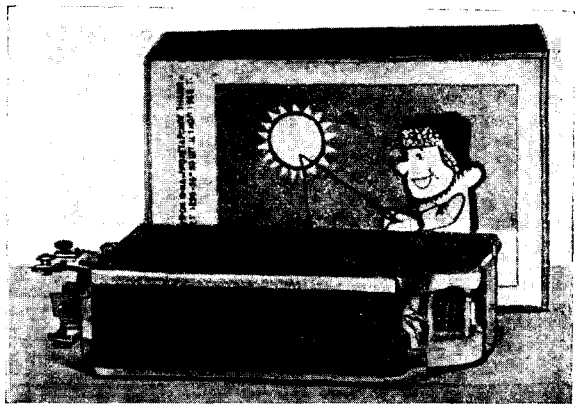

FIG. 5. External appearance of one of the multipliers with focusing in crossed fields.

plate serves as the cathode. The potential difference rises linearly from the beginning to the end of the plates and produces a field intensity E_x which tends to accelerate the electrons toward the collector. By adjustment of the potentiometers in the circuit of the longer working plate and the shorter auxiliary plate, an electric field E_y is produced between them which draws the electrons from the working plate. In the presence of a magnetic field of intensity H, the trajectory of the electrons in the multiplier is a set of portions of elongated cycloids with a step ζ determined by the quantities $U_{div}(E_x)$, E_y, and H. The multiplier gain K increases with the number of collisions of the electron current with the working plate $m = l/\zeta$ (l is the length of the plate) and with the quantity $\sigma\epsilon$, where $\epsilon = U_{div}/m$ is the energy gained by the electrons in one step. Increase of m by changing only H or U_{div} is accompanied by a decrease in ϵ, and K should be an extremal function of these quantities. K can increase monotonically only for parallel or opposite changes of U_{div} and H.

The existence of a magnetic field is not a necessary

condition for obtaining amplification with emitters having low values of σ. If the distance between the plates is decreased to 1/30—1/100 of the length of the plates, and identical voltages are placed across the two plates, then electrons emitted from one plate as the result of incident radiation move in parabolic paths under the influence of only the electric field, reach the opposite plate with sufficient energy gain, and are multiplied[13,33,36] (see Fig. 4b). After m collisions the electron shower is collected on the collector. These multipliers have received the name slot multipliers (Fig. 6).

A similar pattern of electron flux amplification is observed also in channel multipliers, which consist of a small tube coated on the inside with a conducting emitter layer, with the same ratios of channel length to internal diameter (channel caliber) as used in slot multipliers.[34,35,37-41,50] The gain of the multiplier should be an external function of U_{div} and the caliber, for the same reasons as in magnetic multipliers.[37,38] These multipliers are extremely compact. For example, multipliers with an internal diameter of 0.1 mm or less and a length of a few mm are well known.[34] They can be assembled in blocks[34,38,51,52,155] which can be used as a brightness amplifier[52,155] with a resolution determined by the diameter of the tubes, or as multichannel multipliers. In assembly of blocks, it is difficult to make the calibers of all the tubes exactly the same and to provide exactly the same gain in them. However, if the optimal values of caliber are chosen, the requirements in the accuracy of reproducing the caliber are reduced.[38] Both channel and slot multipliers, however, have two important disadvantages. In the first place, the cathode area, which consists of the initial portion of the channel or slot, is small. In the second place, the direct visibility from the collector to the multiplier entrance makes possible strong optical and ion feedback, which leads to a sharp rise in background in the multiplier as U_{div} is increased. Bending of the plates or channels[40] reduces the feedback, but considerably complicates fabrication of the multipliers.

Practically all secondary-emission multipliers are affected by the presence of magnetic fields. Thus, a field of 10 G may reduce the gain of a multiplier with trough-shaped dynodes by a factor of 100.[9] In multipliers with jalousie-type dynodes, an increase of the field to 80 G results in reduction of K by a factor of two.[102] Therefore, as a rule, design of the detector unit must include magnetic shielding of the multiplier.

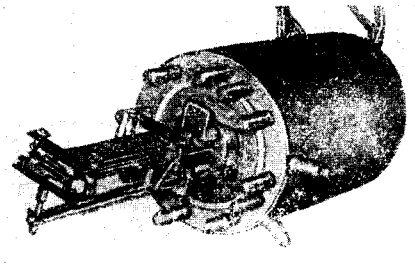

FIG. 6. External appearance of one of the slot multipliers, [13] mounted on the flange of an instrument.

2. Methods of Radiation Detection

Open-type secondary-emission multipliers are a detector intended mainly for recording low-intensity radiation fluxes. For this reason, the choice of operating conditions becomes particularly important.

Two classes of operating conditions are possible with electron multipliers: use of the average output current, and counting of individual pulses produced at the output by the interaction of radiation with the cathode material, as the result of which at least one electron is emitted into the vacuum (the effective number of events is N_0 counts/sec).

In the first case, the flux of electrons ejected from the multiplier cathode by the radiation is amplified by its multiplier system and, for a high gain K, is recorded by a panel meter or chart recorder (Fig. 7). If the gain of the multiplier is insufficient for use of these devices, the signal is further amplified by a dc amplifier.

The principal operating characteristics are the dependence of the output current i_0 (or K) on the potential difference across the voltage divider (U_{div}), the dark current, the linearity of the output current, and its stability under the action of air on the detector, during extended operation of the multiplier, and under heavy current loading of the multiplier. The voltage supply must be stabilized, since the variation of U_{div} determines the output signal stability. The relative mean-square fluctuations of the output of a multiplier[53,47] are determined by input current fluctuations resulting from superposition of the fluctuations of the recorded radiation and fluctuations in the number of electrons ν ejected in a single event, and by fluctuations in the gain of the multiplier.

In the second case, electrons leaving the cathode simultaneously in a single event are amplified by the electron multiplier and produce a voltage pulse in its output RC circuit. If the time constant formed by the parasitic capacity C_p and the load resistance R_L (see Fig. 7) is much longer than the duration of the current pulse of the multiplier ($\leq 10^{-8}$ sec), then the pulse height is $V_{pulse} = Q/C_p$ (Q is the charge received from the electron shower); the rise time of the output pulse is of the order of the length of the current pulse

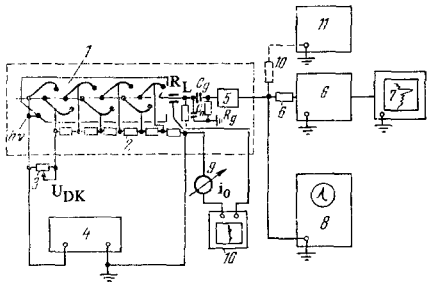

FIG. 7. Block diagram of radiation detection by means of a multiplier. The dashed line surrounds the elements located in the vacuum chamber. 1—Multiplier with enclosure; 2—voltage divider; 3—potentiometer for controlling cathode-dynode potential difference; 4—0—5000 V adjustable, stabilized power supply; 5—preamplifier (cathode follower); 6—counting-rate measuring circuit with remote probe; 7—chart recorder; 8—oscillograph; 9—microammeter; 10—recording microammeter; 11—scaling circuit.

in the multiplier, and the fall time is determined by the time constant of the parallel combination R_L, R_g (see Fig. 7) and C_p.[54] The pulses from the multiplier are sent through a preamplifier (see Fig. 7) to the input of a scaling circuit or counting rate meter, which normalizes them in height and counts each pulse regardless of its height, provided that it exceeds the threshold of the scaling circuit but does not exceed a maximum value V_{max} determined by the dynamic range of the counting circuit (the ratio of the maximum and minimum pulses), and also provided that the pulse duration $t_{pulse} \ll 1/N$, where N is the counting rate of pulses recorded by the circuit and $1/N \gg t_{res}$, where t_{res} is the resolving time of the counting circuit. If these conditions are not observed, there is a loss of counts whose magnitude can be determined from statistical relations (see for example the book by Lewis[55]). If the conditions are satisfied, the value of N will be equal N_0 with an accuracy limited by the loss in the multiplying system and in the counting circuit.

The main operating characteristics are the counting characteristics and also the stability of the counting rate and the number of background pulses. As a result of the statistical nature of the electron trajectories in the multiplier and the secondary-emission process, the pulses at the multiplier output have an appreciable spread in height.[57-59] Therefore as U_{div} is increased, the counting rate first rises monotonically (as the average gain increases), since more and more pulses exceed the counting circuit threshold. Then, when $V_{pulse,min} > V_{thr}$, a plateau in the characteristics is observed, with a slope determined mainly by the change in the number of background pulses. The plateau extends to the value of U_{div} at which either $V_{pulse} > V_{max}$, or the background rises rapidly, or (in systems with continuous emitters) an appreciable decrease in gain occurs. The existence of the plateau permits operation without stabilization of the multiplier voltage source.

From what has been said we can conclude that the pulse-counting method is best for secondary-emission multipliers, since in this case (for operation on the plateau) the experimental results are not affected by variations due to the action of air or of the electron beam, which can be important in multipliers of the open type. Furthermore, in this method it is necessary to take into account only the fluctuations in the radiation flux being recorded, which can be evaluated[56] as $\delta = (Nt)^{-1/2}$ or $\delta = (2N\tau)^{-1/2}$ (δ is the relative mean-square fluctuation, t is the measurement time, and τ is the time constant of the integrating device which measures the counting rate).

However, in operation of a multiplier in this mode, for a counting-circuit threshold of 1—5 mV, it is desirable to have a multiplier gain of 10^6—10^7.

The output parameters obtained for the two detection methods are related to each other and to the current density of the recorded radiation I_0 (photons/sec-cm^2, electrons/sec-cm^2, or ions/sec-cm^2) by simple relations which can be obtained by consideration of the expression for the average current at the multiplier output:

$$i_0 = i_c K = e\bar{\nu} N_0 K = e\bar{\nu} N K' = e\varkappa a a_0 S I_0 K', \tag{1}$$

where i_c is the current from the multiplier cathode, e is the electronic charge, K is the multiplier gain,

$$N = N_0 a a_0 = I_0 S \varkappa_p a a_0, \tag{2}$$

$$a = a_1 a_2 a_3 \tag{3}$$

is the efficiency of the dynode multiplier system, which is determined by the electron collection efficiency in the cathode-dynode region (a_1), in the dynode-dynode region (a_2), and the probability of emission from the first dynode of at least one electron (a_3);

$$a_0 = a_{01} a_{02} \tag{4}$$

is the counting circuit efficiency, which is determined by the relation between the counting rate and the finite time resolution of the circuit (a_{01})[55] and the relation between the width of the pulse-height distribution from the multiplier and the dynamic range of the circuit (a_{02}),[58]

$$K' = i_0/e\bar{\nu}N = K/aa_0 \tag{5}$$

is the multiplier gain in the pulse-counting mode (for one counted pulse), S is the effective illuminated cathode area,

$$\varkappa_p = N_0/SI_0 \tag{6}$$

is the counting efficiency in the cathode material (pulse quantum yield),

$$\varkappa = \bar{\nu}_0 \varkappa_p \tag{7}$$

is the radiation conversion coefficient in the cathode material, which is equal to the quantum yield γ (electrons/photon) in detection of electromagnetic radiation, to the value of σ in detection of electrons, and so forth.

From Eqs. (1) and (2), the expressions for the radiation detection efficiency for the current-measurement and pulse-counting modes will be respectively

$$\beta_c = \varkappa K = \varkappa_p \bar{\nu} K \tag{8}$$

and

$$\beta_p = \varkappa_p a a_0. \tag{9}$$

The quantities entering into these expressions can be determined individually by calculation and from the corresponding characteristics of the multiplier. This permits separate study of the characteristics of the dynode systems (for example, in one-electron events for $\bar{\nu} = 1$) and cathodes, analysis of the sources of error in radiation detection, and prediction of the detector reaction to any form of radiation.

Specifically, in detection of another type of radiation or with another cathode, the multiplier output current should change by a factor $\varkappa_1/\varkappa_2$, the average pulse height by a factor $\bar{\nu}_1/\bar{\nu}_2$, the counting rate by a factor $\varkappa_{p_1}/\varkappa_{p_2}$, and the width of the pulse-height distribution in accordance with the approximate expression[53,101,12]

$$\frac{\overline{\Delta K^2}}{K^2} = \frac{\overline{\Delta\varkappa^2}}{\varkappa^2} + \frac{\overline{\Delta\sigma^2}}{\varkappa\sigma(\sigma-1)} \approx \frac{1}{\varkappa}\left[1 + \frac{2}{(\sigma-1)}\right],$$

where $\overline{\Delta K^2}$, $\overline{\Delta\varkappa^2}$, and $\overline{\Delta\sigma^2}$ are the mean-square fluctuations of K, $\varkappa$, and σ, respectively.

A method of measuring the quantities entering into Eqs. (1), (8), and (9) is provided by Eqs. (2)—(7). In particular, it follows from (5) that for operation of a

multiplier on the plateau of the counting characteristics for $\nu = 1$, it is possible to determine $K' \approx K$ by measuring only the output parameters of the multiplier (N and i_0). This is important, since the permissible output current of a multiplier is limited, and it is difficult to measure the small input currents.

III. MULTIPLIER SYSTEM MATERIALS AND THE PROCESSES WHICH DETERMINE THE VARIATION IN THE CHARACTERISTICS OF THESE SYSTEMS

There are two methods of providing specified characteristics of secondary-emission multiplier systems and stability of these characteristics, i.e., stability of K, aa_0, pulse-height distribution, and so forth, during exposure of the emitting surfaces of the multiplier to air, the electron beam, and other influences. Changes in these characteristics are determined mainly by changes in the secondary-emission coefficient of the emitting surfaces of the multiplier. The first method consists of periodic activation of the multiplier system, carried out directly in the research apparatus.[27] If the multiplier system is fabricated from alloys of magnesium with aluminum, silver, or copper, then a simple heating to 300–450°C in the residual gases (at 10^{-4}–10^{-5} mm Hg) should result in restoration of the emitting layer (MgO) and the multiplier characteristics.[47] However, in this case the apparatus is more complicated, and performance of absolute measurements requires calibration of the detector for each measurement, as the result of the nonreproducibility of the gain K from activation to activation and the possibility of irreversible changes in the cathode characteristics. Therefore, most investigators prefer to construct multipliers which do not require activation in the apparatus and which preserve their characteristics without change for a rather long period.[25-43] For this purpose, the emitters of the multiplier must have stability against the action of both air and current.

1. Emitter Materials. Change of σ in Emitters on Long Exposure to Air

Possible causes of the change in secondary-emission coefficient of emitters on exposure to atmospheric air are oxidation of the surface, change of the layer as the result of oxidation of the excess of metal or solution of gas in it, formation of hydrates, and also increase in the layer of the concentration of crystal lattice defects of the dislocation type,[61] which are traps for electrons with a discrete energy spectrum[62,63] and change σ substantially. Occurrence of these defects is possible in layers obtained by oxidation of metals or alloys.[64] In these layers, mechanical compressive strains[65,66] can occur, which are greater, the more the ratio of the volumes per atom in the layer and in the substrate (α) and the ratio of the coefficients of thermal expansion of the substrate and the layer (ρ) exceed unity. The stresses arising are reduced in the process of forming and cooling the layer,[65] as the result of creation of a definite concentration of defects, but there are evidently residual stresses[65] which can[67] be further diminished on absorption of air, as the result of a change in the energy of the system on the surface of the emitter.

Thus, the problem is rather complicated, and in order to achieve constancy of the parameters of the emitting layers under the action of air, they must be completely saturated with oxygen, not appreciably hygroscopic, stable, should have coefficients, α and ρ as near as possible to unity when formed by oxidation, and should have protective properties with respect to further oxidation, i.e., should not have pores and cracks and should have a low rate of diffusion through the layer at room temperature.[64] It is also desirable that the emitters have the largest possible σ and a high photoelectric work function. It is extremely difficult to satisfy all of these conditions in one emitter. However, in accordance with what we have said, choice of emitting surfaces of nonhygroscopic oxides with good protective properties is the best justified requirement.

Many studies have been made[28,37,61,63,68-74] of the stability of various emitters. In practice, three principal groups of materials are used.

The first group of emitters used includes semiconducting layers of tin oxides,[32,68,76] mixtures of oxides,[85] silicon alloyed with gold,[33] aluminum activated by molybdenum,[36] and also layers on the surface of lead-silicate glasses reduced in hydrogen,[69] and certain other glasses.[52] All these can be used in secondary-emission multipliers with complex emitters. At the present time the best layers are apparently those on lead-silicate glass. These layers have a resistance of 10^6–10^9 ohms, which does not depend on the pressure of the surrounding medium, and have parameters which are constant over the layer.[68,69] They also have the smallest temperature coefficient of resistivity[69] and can transmit the greatest currents without destruction of the layer at potential differences up to 5000 V. The plates can be heated in air up to 400°C and washed in ordinary solvents. However, these layers, like the emitting layers of the entire group, have a σ of no more than 3.5–3.8 (Fig. 8).

The second group of emitters consists of "pure" alloys (CuBe)[29] and metals (Al)[30] which, however, either as the result of the action of air or as the result of preliminary heating in the residual gases, are covered with a very thin protective oxide layer (25–50 Å), consisting of BeO an Al_2O_3, respectively, which preserves the surface from change on further interaction with air or on outgassing by electron bombardment. Since the layer is very thin, it hardly participates at all in producing the secondary emission and σ_{max} does not exceed 2.8–3.2 (curve 4 in Fig. 8).

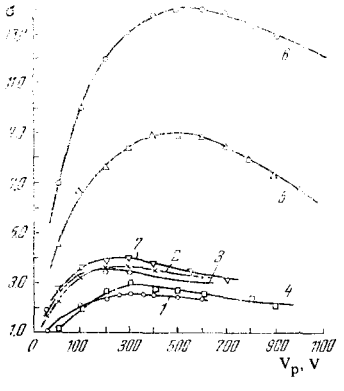

FIG. 8. Values of secondary-emission coefficient for several emitters. 1–SnO_2 with a large excess of metal, R = 3 × 10^4 ohms; 2–SnO_2 with smaller excess of metal, R = 3.2 × 10^9 ohms; 3–lead-silicate glass, reduced in hydrogen, R = 1.2 × 10^7 ohms; 4–beryllium bronze, cleaned by eletrolytic etching and heating at 450°C and a pressure of 10^{-5} mm Hg; 5–layer of BeO on CuBe with normal emission; 6–layer of BeO on CuBe with anomalous emission; 7–layer of BeO obtained by oxidation of metallic Be.

Therefore, this group of emitters is used in those multiplier systems which permit a considerable increase in the number of stages.[25,29]

The low values of σ_{max} in the emitter groups discussed and the adequate stability of the emitting layers result in the fact that the change in σ on being kept in air for several hundred hours usually does not exceed the accuracy of the measurement. For example, for emitters of lead-silicate glass the change in a year of aging amounts to 6%.[69]

The last group of emitters includes layers of alkali earth metal oxides which, being materials with an appreciable width of forbidden band and a low electron affinity (0.5 eV), have large secondary-emission coefficients. Beryllium oxide is principally used, since magnesium oxide and, even more, strontium and barium oxides interact rather strongly with the moisture in air.

Not all means of preparing BeO layers are equally good. In fact, for layers of BeO on Be, as a result of their high degree of imperfection ($\alpha = 1.86$, $\rho = 1.23$)[70] the value of σ_{max} does not exceed 4.5 (curve 7 in Fig. 8), while for the same layers obtained by cathode sputtering of Be in flowing oxygen, σ_{max} reaches 7—10. However, it is difficult to deposit such layers on bent multiplier dynodes. Therefore, in preparation of emitters with these layers, it is necessary to resort to selective oxidation (at $T \geq 450°C$ and an oxygen pressure of 10^{-2} mm Hg) of alloys[64] with beryllium as the active metal, as the result of which a BeO layer 500—1000 Å thick[72,73] is formed on the surface. From the point of view of stability against the action of air, the ideal emitter would be on a substrate having ratios to the oxide $\alpha \approx \rho \approx 1$. Actually, the σ of layers of MgO (for V_p up to 300 eV) produced by selective oxidation on thin layers of Au (with respect to which they have $\alpha \approx 1.1$, $\rho \approx 1$) deposited on magnesium bronze is practically unchanged after 200—300 hours of aging in dry air.[74] For the same layers formed directly on bronze ($\alpha = 1.58$, $\rho = 1.22$), the change in the same length of time is 20—30% or more.[71,74,28] However, for beryllium oxide, substrates with such close correspondence do not yet exist and the best alloy is beryllium bronze ($\alpha = 1.16$, $\rho = 1.58$). In layers formed on this alloy at a high activation temperature, residual mechanical stresses and appreciable concentrations of electron-trapping defects can exist[62,63] (ρ is large), which produces noticeable changes in σ on extended aging of the emitters in air,[8,71] and features which are specific to these layers.[70] In particular, post-emission electrons can be observed, with delay times up to 100 μsec, which increases the background of the multiplier.[70] If an "optimal" concentration[70] of excess beryllium[75] is present in the emitting layer in addition to the defects mentioned, then emission of electrons from close lying centers[77,78] is possible, for example, as the result of the Auger mechanism, and the anomalous component of the emission can arise. This component[70] appears as an increase by 20—30% in σ_{max} (see Fig. 8), in the presence of post-emission electrons, and in certain other effects. This emission is unstable; as the emitter is aged, it can appear and again disappear. These undesirable effects can be reduced to a minimum if in preparing emitters we take measures to reduce the concentration of crystal defects in the layer; annealing and additional oxidation at a temperature lower than the activation temperature.[73] Beryllium oxide layers prepared in this way have values $\sigma_{max} = 8—12$ (see Fig. 8) and properties characteristic of pure dielectric layers of BeO. The variations of σ in individual emitters usually do not exceed 5—6% during the first 150—350 hours of aging either in dry or moist air, after which there is no change at all.[73] This change is appreciably smaller than for beryllium bronze emitters activated by other means, for which the change in σ can amount to 12—16% in the first 24 hours of aging[72] and 20% or more after 150 hours.[8,71]

2. Variation of σ in Emitters During Extended Operation in a Multiplier. Stability of Emitters Under Current Loading

During extended operation of a secondary-emission multiplier the σ of its emitting surfaces may change during bombardment by electrons, principally either as a result of deposition on them of the decomposition products of oil and grease vapors[79,80] or as the result of dissociation and coloration[81] of these layers.

If the vapor pressure of diffusion pump oil, vacuum cements and greases, and other organic materials in the measuring system is rather high during operation of the multiplier, then the first cause of reduction in σ is the principal one. The thickness of the layer of decomposition products grows in proportion to the partial vapor pressure, the current in the primary electron beam, and the time of bombardment.[86,87] With increased emitter temperature, the rate of formation of this layer decreases, and for $T > 250°C$ it generally does not form.[86] The values of σ for layers of grease are 2.6—2.8.[88] In the presence of the decomposition products, σ is still lower (~ 1.8). Therefore, the formation of layers of decomposition products has a particularly strong effect in emitters with a high value of σ (MgO, BeO) and somewhat less in emitters with a low value of σ. In addition, the layer can become charged and reduce the operating stability of the multiplier.

By careful freezing out of organic vapors, this source of variation in σ can be reduced to a minimum. In this case the main cause of variation of σ in emitters with oxide emitting layers under electron bombardment is dissociation of the material of the emitting layer and accumulation in it of dissociation products.[89-95] This cause is effective (at appropriate current densities) in the case when the tests are made under high-vacuum conditions[94,95] and even if the emitters (as in photomultipliers) already contain an excess of metal before bombardment.[94] Furthermore, the emitting oxide surfaces of secondary-emission multipliers subjected to the action of air are similar in their properties to dielectrics, and their dissociation under electron bombardment leads to appearance in the layers of color centers,[81,96] identical to those arising in the presence of an excess of metal and oxygen[75] and easily detected by the existence of fea-

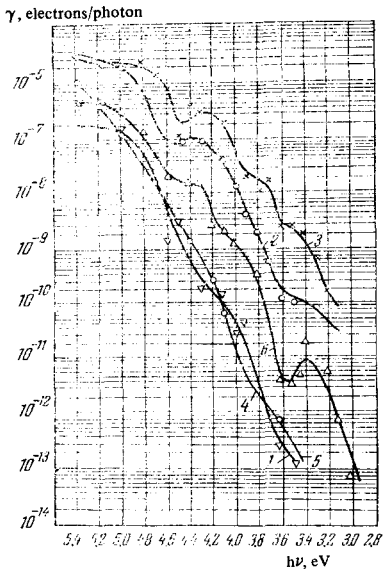

FIG. 9. Change of spectral characteristics of the photoeffect from beryllium oxide after electron bombardment. 1—Before bombardment, thickness of layer 1000Å; 2—after heating to 100°C with heating of the electron gun filament; 3—after electron bombardment at $j = 5 \times 10^{-4}$ A/cm², $V_p = 700$ eV; 4—24 hours after bombardment; 5—before bombardment, for another sample, thickness of layer 500Å (agrees with curve 4); 6—24 hours after bombardment at $j = 5 \times 10^{-5}$ A/cm².

tures in the spectral characteristics of the photoeffect[81] (Fig. 9). In secondary emission, formation of these centers is possible both as the result of electron capture by existing defects of the crystal lattice, and by the mechanism proposed by Warley[83], according to which ionization by electrons of anion sites provides the possibility for atoms to transfer to interstitial sites with formation of color centers both in these sites and in the vacated sites. The changes in σ are evidently determined mainly by centers with photoelectric work function <4 eV.[81] Then, according to theoretical arguments[82] which have apparently been confirmed experimentally[81], σ should vary in accordance with the expression

$$\sigma \sim (n_0 + n_t)^{-1/2}, \qquad (10)$$

where n_t is the concentration of color centers produced in the layer during a bombardment time t, and n_0 is the concentration of centers before bombardment. The resistance of the emitting layer changes at the same time. If recombination of the centers occurs according to monomolecular or bimolecular laws,[81,96] then correspondingly

$$n_t = n_1 (1 - e^{-B_1 t}) / B_1 \quad \text{or} \quad n_t = (n_1 B_2)^{1/2} \operatorname{arcth} [(n_1 B_2)^{1/2} t], \qquad (11)$$

where B_1 and B_2 are recombination coefficients of the centers, and n_1 is the rate of production of centers for a given current density j [$n_1 = f(j)$].

The experimental data[81,96] are in agreement with the ideas developed. Actually, the variation of σ with time is described by one of equations (11) or initially by the first one and then by the second, and the dependence of the established value (for $t \to \infty$) σ_{inf} on j for current densities from 10^{-7} to 10^{-4} A/cm² is represented on a logarithmic scale by a broken line in the general case.

With increase of j up to some critical value $j_{cr\,1}$ the values of σ change only slightly; on the basis of Eq. (10) for $t \to \infty$ this should correspond to $n_0 > n_t$. Then follows a region with a slope close to 0.25, or $\sigma \sim j^{-1/4}$, after which for $j > j_{cr\,2}$ the slope is close to 0.125, or $\sigma \sim j^{-1/8}$. If we take into account that for $j < j_{cr\,2}$ σ varies mainly according to a monomolecular law, and for $j > j_{cr\,2}$ apparently according to a bimolecular law, then if B_1 and B_2 are constant and $n_t > n_0$, we have $n_1 \sim j^{-1/2}$.

We can conclude from the discussion above that the achievable output current of multipliers corresponds to $j_{cr\,1}$. This value depends on the emitter material (Fig. 10) and is greater if n_0 and B are greater, and also the smaller the concentration of crystal lattice defects produced by compression of the emitting layer. However, in general the range of variation of $j_{cr\,1}$ for emitters which are stable to the action of air is not large. In fact (Fig. 10), for many materials studied, including metallic emitters with very thin oxide layers (curve 6 in Fig. 10), these values range between 1×10^{-6} and 3×10^{-6} A/cm². In the case of metallic emitters which have been in air for a long time, the change of σ on electron bombardment may also be due to partial outgassing.[98] Only for SnO_2 with a considerable excess of Sn does $j_{cr\,1}$ increase to 10^{-5} A/cm² (curve 1 in Fig. 10). However, as the resistance of the layer increases to 10^6—10^8 ohms, $j_{cr\,1}$ is reduced to values characteristic of the remaining emitters studied (curve 2 in Fig. 10). Therefore, although in principle methods exist of improving the characteristics of the layers[76] (for example, alloying and so forth), at the present time all the emitters used, when freshly prepared, do not differ significantly in their stability under electron bombardment. The low permissible current densities obtained ($j_{cr\,1}$) are apparently due to the dielectric nature of the emitting surface layers, which distinguishes emitters used in open-type multipliers from those used in photomultipliers.

Extended action of air on emitters, as a rule, reduces the value of $j_{cr\,1}$ somewhat further. For alloy emitters, in addition, a maximum sometimes appears in the function $\sigma = f(j)$, which is apparently due to ap-

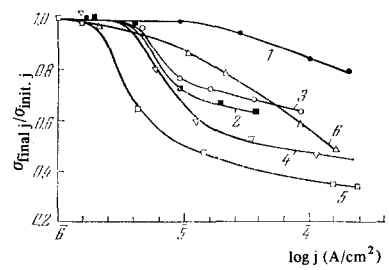

FIG. 10. The ratio $\sigma_{final\ j}/\sigma_{init.\ j_{min}}$ as a function of current density for several emitters ($V_p = 500$ eV). 1—SnO_2 with high metallic content, resistance of layer (R) several hundred ohms; 2—SnO_2 with less metallic content than in 1, $R = 2.8 \times 10^8$ ohms; 3—SnO_2 + 5%In, $R = 4.7 \times 10^8$ ohms; 4—conducting layer on glass reduced in hydrogen, $R = 3 \times 10^7$ ohms; 5—layer of beryllium oxide on CuBe; 6—beryllium bronze, cleaned by electrolytic etching and heated in vacuum.

pearance of the "anomalous" component of emission on reaching the optimal ratio between the concentration of crystal lattice defects arising in exposure to air and the concentration of color centers arising in electron bombardment.[54]

3. Influence of Certain Other Factors on Emitters. Restoration of the Properties of Emitters

Most emitting layers used in secondary-emission multipliers have adequate density, are chemically stable, and have the maximum possible saturation with oxygen. Therefore the changes in σ of emitters, for example of CuBe, during extended aging in air, in an atmosphere of inert gases, and in a rough vacuum[73] are similar. Their characteristics do not change as the pressure in the measuring system changes from 10^{-4} to 10^{-5} [106,73] and even to 10^{-8} mm Hg. Emitters of CuMg (AlMg) behave similarly, but only in the absence of water vapor. The high chemical stability and density of these layers, like layers of BeO[156] and MgO on lead glass, permits the suggestion that the change in σ in these layers in the presence of vapors of various materials can occur only as the result of adsorption of these vapors on the surface of the emitters. Here, as the thickness of the adsorbed layer is increased, the σ of the emitters may pass through an extremum[99] and then approach a value characteristic of the adsorbed material.

In a number of cases, for example, when it is necessary to reduce the background level in mass spectrometers, secondary-emission multipliers must be heated in vacuum. Freshly prepared, activated dynodes of alloys can be heated without change in σ up to the activation temperature.[54] In this case the permissible baking temperature for the multiplier is limited only by the thermal stability of its supporting plates. The σ of these emitters, with a sufficient thickness of the oxide layer (1000 Å), is not affected by heating in atmospheres of N_2, CO, CO_2, and dry H_2.[79] Heating in wet H_2 destroys the emitting layer and reduces σ of emitters with layers of MgO by 30%.[79]

However, during extended storage in air of alloy emitters, some concentration of "mechanical" crystal lattice defects can arise in the emitting layers (Section 1), and during extended use in apparatus, color centers may appear (Section 2). This increases the rate of diffusion of active metal from the alloy to the emitting layer and substantially reduces the permissible baking temperature of the emitters.

Thus, extended heating of such CuBe emitters at pressures below 10^{-4} mm Hg to temperatures above 250°C may lead to a substantial change in σ as the result of enrichment of the emitting layer in excess beryllium.[54,61] Emitters of lead glass permit heating in vacuum to 300°C.[69] The permissible baking temperature for emitters of weakly oxidized alloys (CuBe) is only slightly higher, since at temperatures of 400–450°C diffusion of active metal from the alloy through the thin oxide layer begins.

The properties of all emitters are spoiled to a large extent if a glow discharge occurs in the multiplier, for example, on accidental increase of the pressure in the measuring system above 10^{-4} mm Hg. Even the momentary action of such a discharge (2–3 sec) leads to destruction of the emitting layer and reduces σ for CuBe emitters by 10%.[98] The decrease in σ is greater if the current, duration of discharge, or voltage maintaining it are greater.[80]

The properties of alloy emitters can be restored by a repeated activation. While heating for 30–60 min at 340°C in a diffusion-pump vacuum without disassembly of the multiplier is sufficient to reactivate emitters with MgO layers (for example, emitters of AlMg alloy),[27] on the other hand, emitters of CuBe require disassembly of the multiplier and a repeated oxidation at 650°C in an oxygen pressure of the order 10^{-2} mm Hg.[73] Only this treatment will assure oxidation of the excess beryllium in the oxide emitting layer and complete restoration of the emitting properties. Restoration of lead glass emitters requires the formation cycle of the semiconducting layer to be repeated.[69]

IV. CHARACTERISTICS OF SOME MULTIPLYING SYSTEMS. EFFICIENCY OF CURRENT COLLECTION FROM A MULTIPLIER CATHODE

In order to compare the parameters of different multiplier systems, it is desirable to obtain characteristics for excitation of the cathode only by single-electron events, i.e., with irradiation of the cathode by light from lamps with radiation in the near ultraviolet or by low energy electrons. In cases where these conditions are not satisfied, appropriate stipulations are made in the subsequent discussion.

1. Characteristics of Multiplying Systems with Discrete Dynodes

As has been noted earlier, the highest gains per stage can be obtained with multiplying systems using trough-shaped dynodes. Figure 11 shows the gain as a function of potential difference and the counting characteristics[58] for such a system with 14 multiplying dynodes of beryllium bronze (see Fig. 1), activated as described in section 1 of chapter II and mounted on mica.[31] Similar characteristics are obtained with multipliers with a Venetian-blind type cathode mounted on ceramic.[42] The multiplier system has a gain up to 10^9 and a counting characteristic plateau with practically no slope as U_{div} is changed from 3600 to 4600 V. The intrinsic background of the system at a

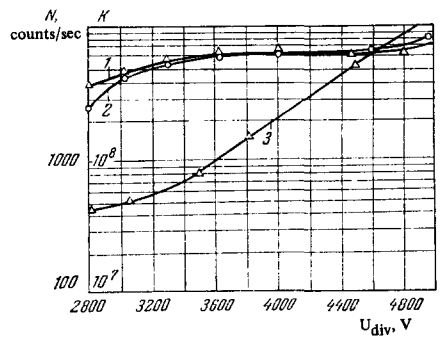

FIG. 11. Counting characteristics and gain of multipliers of beryllium bronze. Counting circuit threshold 1 mV; dynamic range of order 500. 1, 2–$N = f(U_{div})$ for two different multipliers; 3–$K = f(U_{div})$.

pressure of 10^{-6} mm Hg when operating on the plateau is of the order of 6–30 counts/min. With further increase of U_{div} (with increase in K and the output current), the counting rate increases as the result of an increase in the number of spurious pulses of low amplitude which accompany the main pulse. This may result both from ionization of residual gas and from occurrence of post emission[70,100] (See Chapter III). The pulse-height distribution from secondary-emission multipliers, which characterizes the statistical spread in multiplier gain, and the change in this distribution with U_{div}, are shown by the curves in Fig. 12. After the extended action of air (U_{div} = const) the distribution changes approximately from curve 1 to curve 3.[58] The shape of the curves agrees qualitatively with theory,[57] and to avoid missed counts in detection of radiation in the pulse-counting mode it is necessary that the counting circuit have a threshold of the order of 1 mV and a dynamic range of at least 500. The distributions were obtained with β radiation from C^{14} with energies up to hundreds of keV. Therefore, although in this case $\sigma < 1$, in comparison with the single-electron distribution, the distribution is evidently somewhat enriched in pulses of large amplitude. However, as has been shown by calibration experiments with a mercury lamp, this enrichment is not great.

In operation of multipliers mounted on insulating plates, during the first 10–15 min after turning on, the multiplier output current may change by up to 30% of the initial value, after which the change does not exceed 3% per hour.[43] Some variations in counting rate are observed at the same time (respectively up to 12%, and 1%).[43] After the multiplier is turned off and allowed to recover, the process is repeated. Since this initial instability is apparently due to charging of the supporting dielectric plates,[43] it can be reduced by limiting the height of the detected beam of radiation, connection of a metallic shielding enclosure to the multiplier cathode, and reduction of the counting rate below 2000 counts/sec. The initial instability is not observed in multipliers mounted on longitudinal posts.[43] The remaining characteristics of post-mounted multipliers are the same as those given above. The permissible output current for all the multipliers described is of the order of 1 μA (current density 10^{-6} A/cm^2; see Chapter III). At higher currents a monotonic decrease in K is observed with time. The output current and counting rate are linear functions of the intensity of radiation being recorded, up to these output currents.[54]

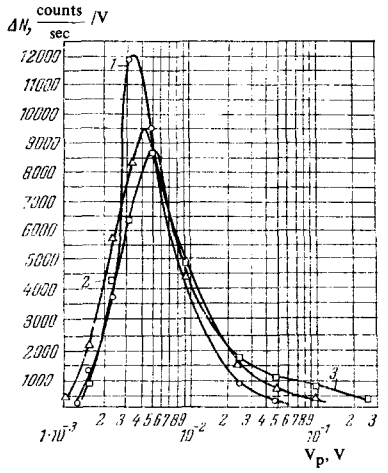

FIG. 12. Pulse-height distribution at the output of a CuBe multiplier for different potential differences applied to the divider. The capacity at the multiplier output is 100 $\mu\mu$F; the source of radiation is C^{14}. 1–U_{div} = 3500 V; 2–U_{div} = 4000 V; 3–U_{div} = 4500 V.

Variation in the multiplier gain with aging usually does not exceed 3–5 times in 2000 hours of aging either in dry or in wet air[73] (see Chapter III) and is practically completed after the first 150–350 hours of aging. With daily use of the multiplier at a pressure below 5×10^{-5} mm Hg with output currents not exceeding 1 μA and daily admission of air to the apparatus, the period of service of the multiplier, determined by the reduction of K from 10^8 to 10^7, usually is more than six months. However, in some cases the gain decreases to 10^6 in the same period but then remains at this level for months or even years.

For multipliers with dynodes with emitting layers also of beryllium oxide but prepared by a different method, the stability to action of air is less and the gain usually does not exceed 10^5–10^6,[8,9,26,98] which leads to deterioration of the counting characteristics.

For multipliers with trough-shaped dynodes of alloys of copper and aluminum with magnesium, with emitting layers of MgO, the gain may reach 10^9 or higher,[28] but the stability to action of air is lower (Chapter III). Thus, in the best multipliers of copper alloys with magnesium, K may change by a factor of fifty after 600 hours of aging in dry air.[28]

Multipliers with dynodes of Al[30] have good stability only for output currents below 1 μA. They have gains of 10^7 for twenty dynodes, which corresponds to a gain per stage of 2.2.

Still lower gain per stage is obtained in multipliers with twenty Venetian-blind dynodes.[29] If the first dynodes are made of Al and the rest of CuBe, the multiplier gain is $\sim 10^5$ at 4000 V.

The permissible output current is also less than 1 μA. By increasing the counting-circuit threshold, the background of the multiplier can be reduced to 50–70 counts/sec.

2. Characteristics of Multiplier Systems with Continuous Emitters

The characteristics of all types of multipliers with continuous emitters have much in common. The most distinct characteristic features of these multipliers can be seen in the example of multipliers of the channel type. For multipliers with straight channels of glass with semiconducting emitting layers, operating at pressures of 10^{-4}–10^{-7} mm Hg, various theoretical calculations of the relation $K = f(U_{div})$ agree to a greater[37,38] degree with the experimental data only for small values of U_{div} (for small K). With increase of K above 10^5–10^6, a sharp increase in gain is observed (Fig. 13) which is not predicted by the simple theory and which is explained[40,34,35,38,103,104,105] by occurrence of positive ion feedback between the output and input of the multiplier. In fact, in this case the gain begins to depend on the pressure in the system and the radiation flux detected, and the rise time of the pulse becomes

step-shaped.[40] In photographing pulses from secondary-emission multipliers with high time resolution it turns out that in fact they consist of a starting pulse and a succession of following pulses.[103] The gain on the basis of the starting pulse is of the order of 10^7—10^8, which is close to the theoretical value, while the total gain of the series may reach 10^{10}. The duration of the series is 1—4 msec,[39,40] and the distance between the pulses in it depends on the residual gas composition: the greater the mass of the gas molecules, the greater the time interval.[103] With increase of the pressure or increase in U_{div}, in addition to the series of pulses, "spurious" pulses begin to appear, which are counted separately from the main series, and then a spontaneous glow discharge may occur.[40] At pressures of 10^{-9} mm Hg (experiments in space rockets) the phenomena described are not observed, the total gain is not so high, and the duration of the pulses does not exceed 10^{-8} sec.[39]

Thus, in secondary-emission multipliers with straight channels in ordinary research apparatus with working pressure of 10^{-5}—10^{-7} mm Hg, the multiplier output current will be rather stable only for $K \leq 10^6$ (U_{div} up to 2500 V). At higher gains the output current and the pulse height produced by the series begin to depend on the pressure, on the intensity of radiation recorded, and so forth. In this case some stability of output signal can be provided by counting pulses in the saturated-output-pulse mode. The saturation phenomenon[40] consists of a limitation of the voltage output pulse produced by the series for K greater than 10^7, as the result of formation of surface charge in the output part of the channel, as the result of intense secondary emission, and redistribution of the potentials along the layer. In this case, increase of K and the output current with further increase of U_{div} occurs mainly as the result of broadening of the pulse. The pulse-height distribution becomes narrow (curve 3 in Fig. 14), and this should provide a good plateau in the counting characteristics of the multiplier. However, the saturation regime does not always produce this effect and is not always preserved sufficiently long. In the first place, the saturation mode sometimes sets in at such values of U_{div} that the number of spurious background pulses is already quite large and the counting rate may fluctuate as the result of change in the number of background pulses with changing pressure, and so forth. In the second place, bombardment of the emitting layers by electrons in operation of the multiplier leads to a gradual speedup with increasing output current of the conversion of distribution 3 (Fig. 14) into distribution 1.[104] In the latter case there is already a substantial number of pulses of small height, and failure to count these pulses can substantially reduce the counting rate relative to the initial counting rate. The shape of the distribution can be restored after several minutes of operation of low intensities, after heating of the multiplier in vacuum, or after exposure to air. However, a slow variation of K by 2.5 times is also observed, regardless of the conditions of operation, as the result of nonuniform heating of the emitting layers in passage of the current along them, and change of the resistance of the layer and the corresponding redistribution of potential along it. In addition, a long-period variation (18 months) is observed in K by a factor of 100, which is not restored by heating.[104]

The negative influence of positive-ion feedback is considerably reduced if the multiplier channel is bent in a radius R = 20 mm for a length equal to $(2/3) \times 2\pi R$,[40] or if the multiplier, with a total channel length of about 50 mm, is made in the form of a helix 8—12 mm in diameter with a pitch of about 4 mm.[103,105] In these multipliers, the theoretical gain relation $K = f(U_{div})$ is in good agreement with experiment even up to $K = 10^8$.[103] As the gain is increased to this limit (for $U_{div} \approx 3000$ V), it does not depend on pressure,[105] the leading edge of the pulse is not distorted, and its rise time is about 20 nsec.[40] All this indicates that in this case the gain is achieved as the result of the theoretically predicted increase in the number and energy of collisions of the electron flux with the emitting layer. The number of collisions reaches 50 (a 1 mm step),[103] and the gain per collision ~1.45—1.5.

In bent multipliers, as in multipliers with straight channels, a limiting of the voltage pulse height is observed[40,103,105] which sets in at $K = 10^7$—5×10^7. However, in this case, saturation apparently occurs as the result of formation in the multiplier channel of space charge, rather than surface charge.[103,105]

The distribution of voltage pulse heights from the multiplier when U_{div} corresponds the beginning of saturation is even narrower in this case than for a straight channel, and even more so in comparison to multipliers with discrete dynodes (even for a gain per stage of 5).[103] However, the distribution broadens somewhat as the intensity of radiation recorded is increased and with further increase of U_{div}. For very large U_{div} (5000 V) an additional maximum appears in the distribution, possibly of ionic origin.[103]

The phenomena described above are observed also for slot multipliers with lead glass emitters having a resistance of 10^8—10^9 ohms. It can be seen from curves 1—2 in Fig. 15 that in such multipliers there is a sharp increase of gain (for $K > 10^5$) due to occurrence of positive-ion and, possibly, optical feedback.[13]

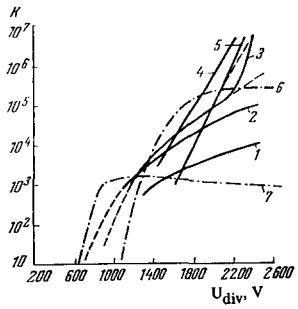

FIG. 13

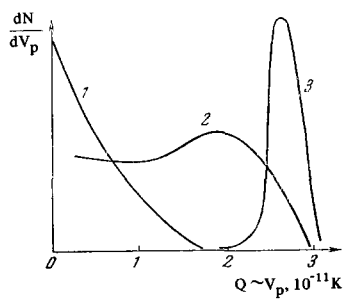

FIG. 14

FIG. 13. The function $K = f(U_{div})$ for a straight multiplier channel. [35] 1—5—Respective experimental data for channel bores of 40, 50, 60, 80, 100; 6, 7—theoretical curves for bores of 50 and 28, respectively.

FIG. 14. Change of pulse-height distribution from a multiplier with a straight channel for operation in the normal mode (1) and with saturation of the voltage pulse height (3). Channel length 5 cm, channel diameter 0.77 mm. [104] 1—U_{div} = 2.5 kV; 2—U_{div} = 3.5 kV; 3—U_{div} = 5.5 kV.

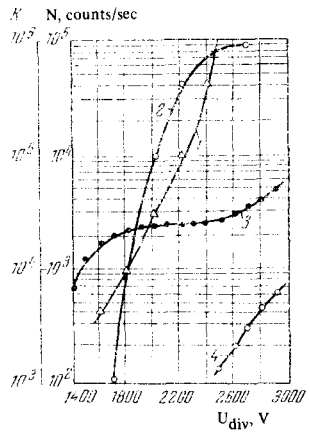

FIG. 15. Dependence of N and K on U_{div} for two slot multipliers with lead-silicate glass emitters. 1, 2—from ref. 13 in detection of Ar^+ ions of 2 keV, ion current 10^{-14} A, respectively $K = f(U_{div})$ and $N = f(U_{div})$; 3, 4—for another multiplier in detection of radiation from a hydrogen lamp, respectively $N = f(U_{div})$ and background.

A sharp increase in counting rate is also observed, as the result of the appearance of spurious pulses produced by this feedback, and at high U_{div} a self-maintaining discharge is observed. Thus, the useful gain does not exceed 10^6 and the counting characteristics have essentially no plateau. However, careful selection of emitter plates, and determination for each pair of plates of the optimum gap (from 0.5 to 1.1 mm) and of the potential difference compensating the decrease in length of one of the plates, permits increasing the useful gain of the multiplier to 10^7 for an emitter length of about 50 mm and obtaining a rather extended plateau in the counting characteristics (curve 3 in Fig. 15). For such a multiplier the appearance of spurious pulses (curves 3 and 4) and the limiting of the pulse height are usually observed simultaneously ($U_{div} \sim 2400$ V). The multiplier background for operation on the plateau is of the order of several counts per second (for a threshold of 1 mV. The permissible output current of the multiplier is 0.1—0.2 μA. With this current, the change in current for a constant radiation flux density is usually no greater than 3—5% per hour of operation, even without preliminary baking of the multiplier in vacuum. Action of air on these emitters and baking in vacuum is sometimes accompanied by fluctuations of K by several times.

A gain up to 10^7 for $U_{div} = 3000$ V is obtained also in slot multipliers with emitters of Al_2O_3 activated by Mo, which have a resistance of 10^8 ohms.[36]

Somewhat higher working gains with somewhat lower U_{div} are obtained with multipliers employing combined magnetic and electrostatic focusing. Multipliers with emitting layers of tin oxides with addition of antimony,[21] which have a resistance of 10^7 ohms, have gains up to 10^8 for $U_{div} = 2000$ V and H = 300 G. For a pressure of 10^{-5} mm Hg, the gain of these multipliers after heating in vacuum drops by 10% after 100 hours of operation at an output current of 10^{-7} A. Heating restores the gain. The gain changes by a factor of 10 as the radiation is scanned from one edge of the cathode to the other. The length of the voltage pulse is roughly 5×10^{-9} sec. However, increasing the pressure in the apparatus shortens the counting characteristics plateau on the high voltage side as the result of appearance of background pulses produced by ion feedback and by appearance of photons in the vicinity of the multiplier collector.[21] The multipliers described by Goodrich and Wiley[32] have $K = 10^7$ at 2000 V and H = 400 G. The potential difference between the working plate and auxiliary plate is 350 V. With a working-plate length of 130 mm, the electron flux undergoes approximately 42 collisions, which corresponds to a gain per stage of 1.48, and the variation of the gain during 8 hours of operation does not exceed ±3%.

Multipliers with lead glass emitters with a resistance of 10^8 ohms and working plate length of about 50—60 mm (see Fig. 5) have gains up to 10^8 at U_{div} = 1800—2000 V, H = 360 G, and a potential difference between the plates of 150—300 V. The background is of the order 1—2 counts/sec. As U_{div} is increased above definite values, a saturation is observed in the pulse height and then an increase in the number of spurious pulses.

3. Efficiency and Accuracy of Detection of the Electron Flux from the Cathode. Absolute Measurements

Like every other radiation detector, secondary-emission multipliers can be used for making both relative and absolute measurements. The latter assume in this case measurements with a given accuracy of the flux density of the detected radiation, which can be translated into energy values if the characteristics of the cathode and source are known. Leaving to Chapter IV for the moment the discussion of the complete accuracy of the measurements, we will discuss now the accuracy of the detection of the electron flux from the cathode.

For relative measurements in the current mode at the multiplier output, this accuracy is determined by the recording device and by the stability of the multiplier system gain (formula (8)) both during operation and storage of the multiplier, and as the energy of the detected radiation is varied. Multiplier stabilities of the order of 1—2% (Sections 1—2, Chapter IV) provided that: the output currents are <0.1—1 μA; the multiplier voltage supply is stabilized to 1% or better; the duration of the measurements is limited (on the basis of the dependence of i_0 on time of operation); the place and angle at which the radiation hits the cathode remain unchanged; the multiplier and its wire leads are shielded; the detected current is sufficient that the statistical fluctuations are less than 1%; for multipliers with continuous emitters the pressure in the device is constant, and the detected fluxes are nearly the same.

In the spectrum of electrons produced by the radiation at the cathode, there are always electrons with energies close to the energy of the quanta of radiation (see Chapter V). If the energy of this portion of the electrons is high, they may be lost for subsequent amplification either because electrons with this energy already are not focused by the existing electric field onto the first dynode (or into the channel) of the multiplier, or because the secondary-emission coefficient of the first dynode is reduced for them (see Fig. 8 and Chapter V) and the probability is increased that they will not excite even one secondary electron. Therefore, in order to assure the accuracy of relative measurements in this mode, it is necessary that the detected radiations do not differ greatly in energy.

Operation in the pulse-counting mode should considerably facilitate the measurements. In this case, for operation on the counting-characteristic plateau, the counting rate is practically independent of K over wide limits (see Fig. 11), and the changes in counting rate with time during the measurements are considerably less than the changes in current. This permits either, by satisfying the conditions formulated above, to increase the accuracy of the measurements, or to increase the time of measurement for each point, i.e., to have the possibility of working at smaller fluxes ($\delta = (Nt)^{-1/2}$).

The situation is more complicated if it is necessary to make absolute measurements of the current from the multiplier cathode. Because of the low stability of the gain, such measurements are possible in the current mode only in the case when, before each measurement, a calibration of the multiplier (determination of K) is made by means of a stabilized source with a known flux density (for example, C^{14}).

Operation of the multiplier in the pulse-counting mode is a simpler matter. In this case the current from the cathode is measured by the number of effective events, and the accuracy with which the number of these events agrees with the number of pulses counted is determined by the closeness to unity and the stability of the coefficients $a = a_1a_2a_3$ and $a_0 = a_{01}a_{02}$ (see Section 2, Chapter II), which can be determined with adequate reliability and without preliminary calibration of the detector. The value of a_3 can be approximately calculated[60] on the basis of Poisson's law[55] for energies of electrons from the cathode less than 200–300 eV and $\bar{\nu} = 1$. In detection of ultraviolet radiation ($\bar{\nu} = 1$) the energy of electrons from the cathode is determined only by the cathode-dynode potential difference (U_{DK}). For multipliers with a gain per stage greater than three for $U_{DK} < 300$ eV, for example for multipliers of CuBe, this quantity will always be close to unity. In fact, for a decrease in gain from five to three as the result of aging of the multiplier or other reasons, a_3 changes only from 0.99 to 0.95.[57] If the energies of the electrons from the cathode are greater than 200–300 eV, the fraction of electrons which do not produce even one secondary electron increases with respect to that calculated from the Poisson curve.[60,107,108] Thus, for Ni with an electron energy of 500 eV, this fraction increases by a factor of two,[60] which, however, for $\sigma = 4$ leads to a decrease in a_3 only from 0.98 to 0.96. For still higher electron energies, determination of a_3 must be made from the experimental data.[60,107,108] The values of a_1 and a_2 can be determined from the dependence of N on the cathode-dynode potential difference (Fig. 16) and the dynode-dynode potential difference, on the assumption that on an extended plateau of these functions with no slope (for U_{div} = const), $a_1 = a_2 = 1$. However, this is true only in the case when the energy of the electrons from the cathode does not exceed that necessary to obtain the maximum value σ_{max} at the first dynode (see Fig. 8). For electrons with higher energies, a spurious plateau can be observed as the result of compensation of the decrease in a_3 for decrease of σ by an increase in a_1 with improvement of the electron focusing conditions.

In addition, complete collection of the electrons can

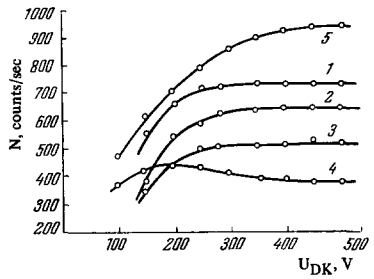

FIG. 16. Counting rate at multiplier output as a function of cathode-dynode potential difference (U_{DK}) for a constant difference of potential on the remaining electrodes of the multiplier. 1–3–For different points of a cathode in the form of a cylinder with R = 8 mm; the curves are displaced with respect to each other by 100 counts/sec. 4, 5–For different points of another cathode with unfavorable conditions of electron focusing.

be considered as proved only if a distinct plateau exists in the $N = f(\varphi_0)$ characteristics (Fig. 17) or in $N = f(x)$, where x is the displacement of the multiplier perpendicular to the beam of radiation. The quantity a_{01} can always be taken as unity at the expense of an appropriate decrease in intensity of the detected radiation. Thus, the product aa_{01} may be extremely close to unity. The quantity a_{02} can be approximately estimated, if the operating threshold and dynamic range of the counting circuit are known, from the pulse-height distribution curves at the multiplier output (the curves of Fig. 12) as the ratio of the area under the curve inside the dynamic range of the circuit to the total area. For small K, mainly low-amplitude pulses are missed, and for large K–pulses of large amplitude. Calculations show that for a change of K of the multiplier from 10^9 to 10^7 as the result of aging or of change in U_{div}, the value of aa_0 changes only from 0.87 to 0.9, if the counting circuit has a threshold of 1 mV and a dynamic range of 500. As the dynamic range is broadened, the value of aa_0 increases.

Thus, in operation of a CuBe multiplier with a well designed entrance system in the pulse-counting mode, and in the plateau of the counting characteristics and of the function $N = f(U_{DK})$, for output currents up to 1 μA and with observation of the recommended precautions, the efficiency for detection of currents from the cathode has a value of the order 0.9, is maintained with an accuracy of the order of a few per cent as K varies over an extremely wide range, and can be determined without special calibration even in the case of single-electron events at the cathode. For many-elec-

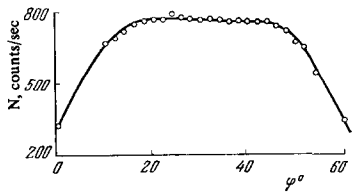

FIG. 17. Zone characteristics of a cathode of Ni in the form of a portion of a cylinder with R = 8 mm. [58] The source of radiation is an ampoule with C^{14}, located at a distance of 1 mm from the multiplier mounting plate closer to the foot of the first dynode. The angle of rotation of the ampoule is measured from one of the feet of the cathode. The beam of radiation has a divergence of 5°.

tron events ($\bar{\nu} > 1$) the missed counts decrease and the accuracy should increase. Thus, for $\bar{\nu} > 3$, the value of a_3 will practically always be unity. In making such measurements with multipliers with a low gain per stage, calibration of the detector is necessary before each measurement. Thus, for an amplification of 1.5–2 ($K = 10^4$–10^6), a_3 decreases already to 0.6–0.8[57] and insignificant variations in K are accompanied by appreciable changes in a_3. In multipliers with continuous dynodes which have a gain per collision of the same order (see part 2 of this chapter), the values of a_3, and also a_1 and a_2, are extremely difficult to determine, as the result of uncertainty in the number of collisions.

V. CATHODES. EFFICIENCY AND ACCURACY OF RADIATION DETECTION

In order to provide stability of measurements under conditions of frequent exposure of the multiplier to air, the multiplier cathodes must satisfy all of the requirements placed on the dynodes, and to provide a low background level they should have a high work function. Therefore cathodes may consist of metals and alloys with a high work function and layers of nonhygroscopic and impurity-free oxides and halides of alkaline earth metals, and also of alkali halide compounds, which have a large width of forbidden band. The efficiency of each of these cathodes can be determined for detection of any given radiation. In this case, to determine the efficiency of the multiplier as a radiation detector (β, β_p), it is necessary to know the efficiency of the multiplying system and its variation with the energy of the radiation. The latter is determined (part 3, Chapter IV) by the energy distribution of the emitted electrons, the direction of emission, and the value of $\bar{\nu}$.

1. Detection Efficiency for Corpuscular Radiation

In detection of electrons by a secondary-emission multiplier operating in the current-measurement mode, the quantity κ is equal to the total secondary-electron emission coefficient (which for $\kappa_p = 1$ is $\bar{\nu}$). This quantity depends on the energy of the primary electrons,[109] and the experimental results must be corrected in accordance with the relation $\sigma = f(V_p)$ (see Fig. 8). The maximum value σ_{max} for well outgassed metals increases from 0.5 for Be to 1.7 for Pt and is reached at $V_p = 300$–800 eV, respectively. For metals and alloys which have not been outgassed, $\sigma_{max} = 2$–3 for $V_p = 500$–600 eV. For alkali halide compounds the maximum values are as high as 20 (CsBr, CsI) for $V_p = 2.0$–2.5 keV, and for beryllium and magnesium oxides up to 12–18. These values are achieved only for an emitting layer thickness at least 500–700 Å (the zone of emission of true secondary electrons) and with well defined conditions of preparation (see, for example, Fig. 8). For these groups of emitters, σ is greater than unity for detected electron energies varying from 50–150 eV up to several tens of keV (Fig. 18),[110,111] which also determines the region in which they can be efficiently utilized as cathodes in secondary-emission multipliers. The region of efficiency can be broadened on the high-V_p side by using cathodes of the transmission type.[112]

The energy distribution of the secondary electrons

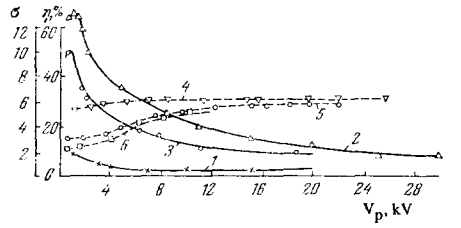

FIG. 18. σ and η as a function of electron energy for several efficient emitters. 1–3–$\sigma = f(V_p)$ respectively for unactivated CuAlMg alloy, [110] activated CuAlMg alloy, [110] and activated CuBe Alloy; [111] 4–6–similar curves for $\eta = f(V_p)$.

emitted by the cathode[109] is characterized by the presence of true secondary electrons with energies up to 50 eV with a peak at a few tenths of an eV or a few eV, and elastically or inelastically reflected electrons with energies from 50 eV up to the energy of the primary electrons. The shape of the distribution changes, slightly, only for $V_p \leq V_{p\,max}$. The distribution of the slow electrons of the first group in direction of emission follows a cosine law for emission from polycrystalline materials. If the cathode surface is not rough, the number of secondary electrons increases with increasing of angle of incidence, especially when Z_{eff} is small and V_p is large (up to 1–2 keV). The fraction η of electrons in the second group, which determines (Section 3, Chapter IV) possible failures to count fast electrons from the cathode, increases with increasing Z_{eff} from 7% for Be to 45% for Au. For normal incidence of electrons on the cathode, the distribution of reflected electrons in direction of emission has a cosine shape. However, for oblique incidence peaks appear in the distribution.[113]

From what has been said, it can be concluded that in detection of electrons it is most suitable to use as cathodes light materials with oblique incidence of the radiation. Thus, beryllium oxide has $\eta \approx 12\%$ and a large value of σ. However, if the emitting layers of BeO are prepared by oxidation of an alloy with a heavy metal, then the value of η noted above is retained only up to $V_p \approx 2$ keV, after which it is already determined by the substrate-alloy (see Fig. 18). Therefore, in operation of multipliers in the current-measurement mode, the results should be corrected not only for σ, but also for variation of η with electron energy.

In the pulse-counting mode, the need for correcting for σ and η disappears (Section 2, Chapter II). In addition, we can expect a counting efficiency $\kappa_p \approx 100\%$ for cathodes (see Section 3, Chapter IV) everywhere where $\sigma \gg 1$. If σ of the dynodes is also greater than three, and for a good entrance system ($a_1 = 1$) and an adequate range of the counting circuit ($a_0 \approx 1$), then $a_3 \approx 1$ and $\beta_p \approx \kappa_p$, since for large values of σ the probability of emission of fast inelastically reflected electrons without accompaniment by slow electrons is apparently small and an effective event will be counted as the result of detection of the latter. The fraction of elastically reflected electrons emitted into the vacuum without accompanying electrons is also small. For metals and, probably, for oxides for a V_p of several hundred or thousand eV, it does not exceed 2–3%.[125] In fact, for emitters of CuBe, $\beta_p = 100\%$ for $V_p = 500$ eV.[8] However, $\beta_p = 40\%$ at 6 keV, 33% at 30

keV, and only a few per cent at V_p = 1–2 MeV, which is lower than the values calculated from the curves of Figs. 8 and 18, apparently as the result of using cathodes which are not optimal ($\sigma_{max} \approx 4$). For still smaller values of σ the efficiency is only 63% for V_p = 320 eV.[114] However, even in this case the variation in efficiency does not exceed a few per cent when the multiplier is kept in air for a period of five months.

In detection of ion and atomic beams by means of multipliers operating in the current-measuring mode, $\kappa = \sigma_M$, where σ_M is the coefficient for ejection of secondary electrons by corpuscular particles. For outgassed metals (Mo, Ni) this quantity is equal[115] to 0.2 for V_p = 200–600 eV and rises linearly from that value with increasing V_p. For unoutgassed metals the linear rise begins at 200 eV, and σ_M is somewhat higher; for V_p = 6 keV, σ_M already reaches values of 2.4 for K^+ ions on Mo, 2 for Ne^+ on Pt, and 2 for Li^+ on Pt.[116] Oxidation of metals and alloys leads to an increase in σ_M. Thus, for V_p = 5 keV and detection of He^+ ions, σ_M of the alloys AgMg, CuBe, and Nichrome, heated 100 hours at 220°C in a vacuum of 10^{-6}–10^{-5} mm Hg, is already 4.5, 4.1, and 3.5, respectively.[117] For well oxidized AgMg alloy the dependence of σ_M on energy is shown in Fig. 19 for several ions for V_p up to 10 keV. Further increase of V_p up to several hundred keV (with a cathode of oxidized CuBe[98]) for H^+ ions leads to appearance of a gentle peak in σ_M at 100 keV, which is twice the value at 5 keV. For the heavier N^+, σ_M increases up to V_p = 160 keV and is seven times the value at 5 keV. For small V_p (up to 6–25 keV), σ_M for light ions is higher than for heavy ions, and for large V_p–the reverse.[9,98] Therefore at small V_p (2 keV), σ_M drops with increasing ion mass, and at energies of 4–10 keV there is a maximum in this function and a region where σ_M is constant.[9]

For $V_p \leq 5$ keV, positive ions and the corresponding neutral atoms have similar values of σ_M.[9,118] The yield of secondary electrons under the action of negative ions is higher,[9] but on outgassing of the cathode the differences decrease.[119] Increase of the ionic charge leads to an increase in σ_M.[9] Molecular ions, particularly complex ones, produce more secondary electrons than atomic ions.[9,98,118,120] Thus, in the transition from H^+ to H_2^+ (at 100 keV) the yield increases by 1.5 times, and in going from Hf^{178+} to $C^{14}H^{10+}$ with the same mass–by a factor of two (at 9 keV).[9,120]

Most authors[9,118,121] indicate a change in σ_M in the transition from one isotope to another. Therefore an isotopic ratio measured by means of the output current

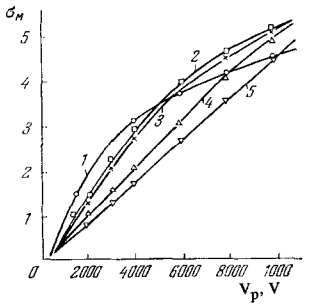

FIG. 19. σ_M as a function of energy for several ions. [9] Cathode–oxidized AgMg alloy. 1–Li^+; 2–Na^+; 3–K^+; 4–Rb^+; 5–Cs^+.

of a secondary-emission multiplier should evidently be corrected.[121] The value of σ_M at small V_p (several hundred eV) is practically unchanged as the angle of incidence φ varies,[9] but increases as $a - b \cos \varphi$ for ion energies usually used in mass spectrometry (1–5 keV)[9,116] and as $A/\cos\varphi$ for V_p of the order of 120 keV and above.[97]

The distribution in direction of emission of electrons produced by incident particles from a polymetallic metal follows a cosine law over wide ranges of V_p.[122,123] For unoutgassed cathodes the emitted electrons have energies up to 30 eV and their energy distribution is practically independent of the energy and type of ion, while for outgassed emitters some increase is observed in the number of electrons with energies of 5–30 eV as V_p increases from 200 eV to 1.2 keV.[115]

The stabilities of various cathodes are characterized by the following numbers. For unoutgassed Ni bombarded by 120–212 keV protons, a variation of σ_M by 20% is observed in 10 min.[97] In outgassed Mo σ_M changes by 10% in the course of 3.5 hours after being put under vacuum.[116] For outgassed Nichrome σ_M remains constant for a week of storage in vacuum, but changes appreciably after exposure to air.[117] Cathodes of CuBe have good stability during measurements and for short exposures to air.[98]

In operation of multipliers with CuBe cathodes in the pulse-counting mode, the stability is further increased. In this case for large σ and a dynamic range broader than the pulse distribution curve,[98] correction of the isotopic ratio is not required and β_p = 100% as V_p is changed over a wide range. Thus, in detection of N^+ ions β_p is 92% even at 4 keV and remains equal to 100% for V_p up to 220 keV.[98] For Li^+ ions the efficiency is close to 100% for $V_p \geq 2$ keV.[124] Alpha particles of sufficient energy[53] are recorded with the same efficiency.

Thus, in detection both of electrons and of ions, atoms, and molecules, β_p can be of the order of 100% for particle energies over a rather wide range.

If β_p or κ_p are known, absolute intensity measurements can be made with an accuracy determined by the accuracy with which these quantities are determined.

2. Efficiency for Detection of Electromagnetic Radiation

In detection of electromagnetic radiation with a secondary-emission multiplier operating in the current-measuring mode, $\kappa = \gamma$ electrons/photon. As a result of the great difficulties involved, measurements of the efficiency of cathodes for the spectral region 1.5–2000 Å have been made only recently. However, from studies which have been made of the photoeffect in the soft x-ray, for ultraviolet, and near ultraviolet regions of the spectrum[19,20,46,126-128,134] we can picture the emission process and evaluate the efficiency of a number of multiplier cathodes. Thus, studies of the x-ray photoeffect[129-132] have shown that x-ray photoelectrons, excited by radiation with wavelength 1.54–300 Å, and Auger electrons have sufficient energy and are capable of exciting a substantial number of slow secondary electrons which are emitted simultaneously

into the vacuum. The bunch of electrons produced has an average number of electrons $\bar{\nu}$, including x-ray electrons which have not completely lost their energy. When the cathode is excited by CuK_α characteristic x radiation (1.54 Å) the value of $\bar{\nu}$/(for an angle of incidence ~ 70°) for metals is about 2, and for dielectrics of the order of 12 or even 23–28 (CsI, CsCl).[130] When cathodes are excited by radiation with λ = 13–113 Å,[131] $\bar{\nu}$ reaches 3–7 for dielectrics and 2–3 for metals. In the spectral region 500–5500 Å, evidently $\bar{\nu} = 1$, since in this case measurements of the photoeffect yield based on the total current[46,127,128] and based on the number of effective events[19,20,126] are in good agreement. For λ = 1.54–10 Å the values of $\kappa = \gamma$ are 0.01–0.12 for light metals and 0.07–0.3 for heavy metals.[1] For efficient dielectrics κ is already 1.35–7.8 for CsI and 0.06–0.6 for SrF_2.[1] As λ is increased, there is a tendency for κ to increase, but κ decreases on passing through the absorption edge of a material, and then increases again. For λ = 430–630 Å, κ = 0.3–0.6 electrons/photons (SrF_2, CsI).[46] Further increase of λ is accompanied by a decrease in κ to 10^{-1}–10^{-2} electrons/photon for λ = 1200 Å and to 10^{-14} electrons/photon for $\lambda > 4000$ Å (Fig. 20).

As can be seen from the data presented, even for a limited interval of wavelength the value of κ undergoes extremely important variations, which hinders application of multipliers in the current-measuring mode. Therefore multipliers are usually used in the pulse-counting mode. In the ultraviolet region, $\kappa_p = \gamma(\bar{\nu} = 1)$. In the x-ray region, as the result of the high penetrating power of the radiation, not all photons absorbed by the cathode produce a bunch of electrons. Therefore in this region of the spectrum, in contrast to what is observed in detection of particles, in spite of the large values of $\bar{\nu}$, κ_p may be <1 ($\kappa \neq \bar{\nu}$). As has already been noted (part 3, Chapter IV), in detection of ultraviolet radiation not many counts are missed by the multiplying system ($aa_0 \approx 1$) and $\beta_p \approx \kappa_p$. In the x-ray region, the variation of $\bar{\nu}$ can result in a change of the

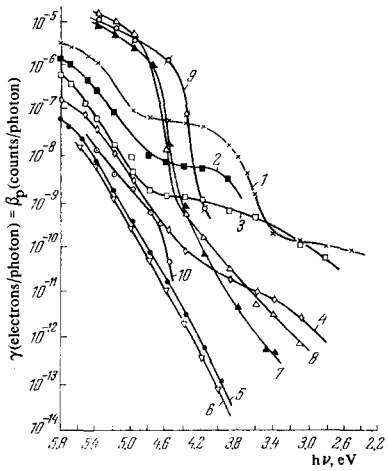

FIG. 20. Spectral characteristics of certain cathodes in the visible and near ultraviolet regions of the spectrum. 1, 2–SrF_2 after and before bombardment at $h\nu > 8$ eV; 3–CsI; 4–BeO on CuBe, oxidized by the standard technique; 5–layer 4 after additional oxidation at 650°C; 6–layer of MgO on CuMg alloy, covered with Pt and oxidized at 650°C; 7–Pt foil heated in air to a white heat; 8–Au foil; 9–layer of Al; 10–layer on lead-silicate glass reduced in hydrogen.

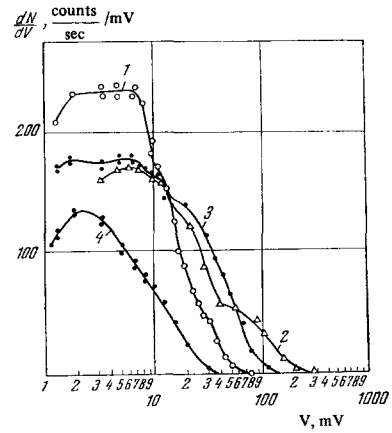

FIG. 21. Pulse-height distribution curves from multipliers on bombardment of NaCl by characteristic lines. The multiplier operating conditions are the same for all measurements. 1–CuL_α–13.3Å, $\bar{\nu}$ = 3.7; 2–OK_α–23.61Å, $\bar{\nu}$ = 6.4; 3–CK_α–44.78Å, $\bar{\nu}$ = 5.6; 4–for bombardment of Al by visible light, $\bar{\nu}$ = 1.

pulse-height distribution curves from the multiplier (Fig. 21), and consequently also a change in a_{02}. In addition, for small values of $\bar{\nu}$ the fraction of bunches in which a fast photoelectron is emitted into the vacuum without accompaniment by a slow secondary electron is large, which leads to decrease of a_1 and a_3. For dielectric cathodes ($\bar{\nu}$ large) the fraction of these bunches is negligible. Therefore β_p is equal to κ_p with an accuracy determined by a_{02}, which, for a counting-circuit dynamic range of about 500 and a threshold of 1 mV, according to Fig. 21 can apparently vary over the spectrum from 0.85 to 0.9. For metal cathodes excited by CuK_α radiation (high photoelectron energies), the number of photoelectric counts missed reaches 40–50%[130] (a_1a_3 = 0.6–0.4). However, as the wavelength is increased the counting loss falls rapidly as the result of the rapid decrease in photoelectron energy.

Values of β_p have been directly determined[1] for multipliers of CuBe with plane cathodes with layers of the material investigated, placed at an angle of incidence θ = 20° to the direction of the radiation. It turns out that the highest efficiencies are obtained with heavy metals and alkaline earth compounds (Au, CsI, CsCl, SrF_2). Thus, for gold at λ = 1.54 Å, β_p = 1.4%; for CsI, β_p = 7.1%; for SrF_2, β_p = 0.8%. As the wavelength is increased from 1.54 Å, the efficiency rises, undergoing a decrease at the absorption edges (Fig. 22), and reaches the following values: for CsI 48% at λ = 11–13 Å, 90% for λ = 120 Å, and 60% for λ = 630 Å; for SrF_2 31% at λ = 44 Å and 39% at λ = 430 Å; the values of β_p for BeO and MgO are only slightly lower (mainly in the short-wavelength region). The accuracy of the measurements is ~10%. If the photocathode configuration is changed, the data of ref. 1 must be corrected for the change in a_1a_3, which is negligibly small for dielectric cathodes. As the angle θ is changed, the data of ref. 1 must be recalculated on the basis of the expression $\kappa_p \sim 1/\sin\theta$[1,130] (for angles θ greater than the angles of total external reflection of the radiation). For storage in air for a month, even such cathodes as CsI and, even more so, BeO, SrF_2, and Au undergo practically no changes in their properties in

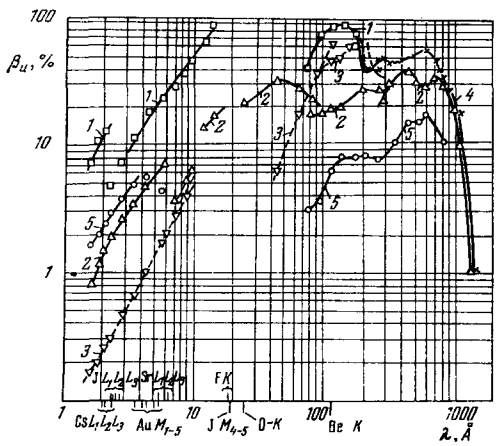

FIG. 22. Spectral dependence of β_p for certain cathodes. 1–CsI; 2–SrF_2; 3–LiF; 4–BeO; 5–Au. 1–10Å region from ref. 1; 10–110Å region from ref. 134; 75–300Å region from ref. 1; 200–900Å region from ref. 46; region > 1000Å from ref. 20. The portions of the spectrum have not been joined together. Absorption edges are marked on the λ axis.

the x-ray region[1] and far ultraviolet region of the spectrum. Changes are observed only in the tails of the spectral characteristics (λ > 1200 Å; see Fig. 20).

From the data presented, we can conclude that the sensitivity of multipliers in the spectral region 1.5–1200 Å is rather high, and the stability of cathodes and our knowledge of β_p permit use of multipliers in absolute measurements of radiation flux with an accuracy determined essentially by the accuracy in measurement of β_p.

As we have noted, heavy cathodes are most efficient over the entire region. However, use of these cathodes makes it more difficult to use multipliers as "solar blind" detectors[20], as the result of the presence in these cathodes of noticeable tails in the spectral characteristics up to the visible part of the spectrum (see Fig. 20). Therefore, for solar blind detectors it is more suitable to use layers of beryllium oxide, whose spectral characteristics undergo less change than other cathodes on extended exposure to air and on bombardment by the detected radiation, and which may have an extremely sharp drop in the spectral characteristic (curve 5 in Fig. 20). However, for λ = 1.54 Å these layers have a low efficiency, although with increased wavelength the efficiency arises to 53% (λ = 580 Å). The properties of heavy efficient cathodes and light solar blind cathodes can be combined into one by covering a heavy compound by a thin layer of beryllium oxide.[133] Deposition of this layer increases β_p in the short-wavelength region of the spectrum as the result of increased efficiency in secondary-electron production and a decreased number of fast x-ray electrons emitted into the vacuum without accompanying secondaries.[133]

VI. SOME EXAMPLES OF MULTIPLIER USE

One of the principal fields of application of open-type multipliers is in mass spectrometry. Here the advantages of secondary-emission multipliers appear in detection of ion currents of 10^{-19}–10^{-12} A and lie in the possibility of increasing the sensitivity of the analysis by 2–3 orders of magnitude,[10,11,136] and in operation in the pulse-counting mode–in the possibility of avoiding correction of the results for variation of the mass and energy of the detected particles. The standard circuit arrangement in a mass spectrometer using a multiplier[11,10] consists of a pulse-counting channel and a channel which measures the ion current with an electrometer, which is used for currents of 10^{-12}–10^{-11} A and which can if needed be connected to the output of a multiplier. The counting rate can be recorded by means of an integrator and chart recorder or point by point by means of a scaling circuit. In order to monitor the counting loss in the multiplying system it is desirable (part 3, Chapter IV) to have the possibility of smoothly controlling U_{div} and U_{DK} and displacing the multiplier with respect to the beam of radiation recorded. In mass spectrometers with multipliers[8] an accuracy of 1% has been achieved in measurement of the isotopic ratios of scandium and other rare earth metals.[135] The measured value of the isotopic ratio is 10^{-5}. In the presence of intermediate isotopes, this number increases. Articles have been published which describe the measurement by means of a multiplier[31] of the isotopic ratio of microquantities of noble gas as low as 10^{-9}–10^{-8} cm^3.[137] The short rise time of pulses in the multipliers (3×10^{-9} sec for toroidal systems, 3×10^{-9} for jalousie systems,[138] and 1×10^{-10} for magnetic systems[25]) permits successful use of multipliers in fast nonmagnetic mass spectrometers,[139,140] in which the entire picture of the mass spectrum is displayed on an oscillograph screen. In these devices it is desirable to use multipliers with plane cathodes or jalousie cathodes with normal incidence of the radiation, since this reduces the dispersion of the time of flight of the particles before they encounter the cathode. The multiplier records extremely high currents in a pulse with a rather low gain (10^5). Therefore (Section 2, Chapter III) in these devices multipliers can be used with a large number of stages of weakly activated alloys (jalousie,[29] box-type,[27] magnetic,[25] or continuous emitters). For analysis of the composition of residual gases in ultra-high vacuum systems, very simple mass spectrometers[141] with multipliers[8] are used. Use of multipliers with a "cold" ion source have been reported.[85] The source consists of a photocathode (Ta) irradiated by light from a hydrogen lamp and a magnetic multiplier with continous emitters, which amplifies the photocurrent and directs a flux of electrons into an ionization chamber. As a result, the spectrum is obtained in purer form as the result of absence of a hot filament, which gives off carbon monoxide on being heated. The combination of a secondary-emission multiplier and a photomultiplier with a scintillator permits a detector to be made with essentially no intrinsic background.[157] The possibility of detecting relatively low-energy particles with high-efficiency multipliers is utilized in nuclear physics. In particular, multipliers with beryllium bronze dynodes have been used to detect recoil nuclei in study of the β decay of free neutrons[142] and various radioactive isotopes,[143] in detection of the products of nuclear reactions occurring on bombardment of targets by protons,[144] and also in study of the angular spectrum of

recoil nuclei arising from bombardment of specimens by 4-MeV deuterons.[145] A superhigh-frequency secondary-emission detector has been developed for heavy charged particles with energies of several MeV[145] with a time resolution of 2×10^{-11} sec, which utilizes a multiplier with copper-beryllium dynodes.[31]

As we have already noted in Chapters I and IV, multipliers have major advantages for use in the spectroscopy of soft x rays with wavelengths of 10–300 Å in vacuum spectrographs with diffraction gratings.[2-4] This region is difficult for experiments because of the low intensities of the radiation sources and the low stability of most objects of study. Use of a multiplier permits substantial reduction in the anode current of the x-ray tube and avoidance of decomposition of the materials studied, and at the same time reduction of the exposure both in emission and absorption analysis. Thus, in the work of Ivanov[146] with a multiplier[31] operating in the pulse-counting mode, the unstable radiation spectrum of sulfur in CdS was obtained in all its details with x-ray tube currents five times lower and an exposure time for point-by-point recording of the spectrum 50 times lower than with a photographic plate. Multipliers are used also in spectroscopy of weak ultraviolet radiation in the vacuum region, 200–1500 Å.[6,20,126] If appropriate cathodes are used (Chapter V), as a result of the extremely low background a multiplier provides a greater signal-to-background ratio than other detectors, even for $\lambda > 1200$ Å, where its spectral sensitivity decreases considerably.

The simplicity, the possibility of covering the spectral region from 1 to 1500 Å with a single detector, the low dependence of the output signal on temperature, the possibility of making absolute measurements, and the possibility of operation in a background of the intense radiation of the Sun in the visible part of the spectrum (Chapter V) make the multiplier a very convenient detector for research with artificial Earth satellites and rockets on the radiation spectrum of the Sun and other objects with low intensity in the x-ray region.[22,23,147] Separation of a portion of the spectrum in such studies can be accomplished both by decomposition of the radiation into a spectrum by means of a diffraction grating,[22] or by means of filters[147] placed in front of the multiplier entrance window. In particular, the sharp drop in the spectral sensitivity of multiplier cathodes[31] in combination with absorbers of LiF and CaF_2 permits construction of narrow-band detectors[20] (Fig. 23) and measurement by this means of the intensity of the important L_α line of hydrogen with a signal-to-noise ratio of seven. Magnetic multipliers with continuous emitters[21] have been used for the same purposes. Multipliers have been used also in determination of the flux and energy spectra of electrons at altitudes of 180–500 km.[24,148]

The possibility, under certain conditions, of making absolute measurements of an extremely small number of electrons emitted from the cathode of multipliers (part 3, Chapter IV) permits obtaining qualitatively new results in various physical studies. This applies first of all to the study of all possible forms of emissions. Thus, use of multipliers in study of photoelectric emission has permitted measurement of the quantum yield of the photoeffect in the near ultraviolet and visible

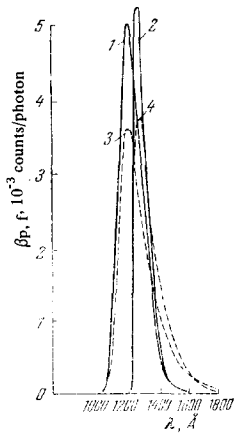

FIG. 23. Spectral efficiency $\beta_{p,f}$ of several detectors of the filter type. [20] 1, 2—Photocathode of MgO with filters of LiF and CaF_2 respectively; 3, 4—photocathode of BeO and the same filters.

regions of the spectrum down to 10^{-14} electrons/photon[19] in the presence of the usual values 10^{-7}–10^{-10} electrons/quantum. This permits study of the photoeffect from impurity centers with extremely small concentrations. Use of multipliers[34] in detection of a modulated signal, which is proportional to the derivative of the volt-ampere characteristic, in automatic recording of photoelectron energy distribution curves has permitted reduction of the necessary saturation photocurrent from 10^{-11} to 10^{-13} A.[149] Use of open-type photomultipliers[31] has also permitted significant extension of our knowledge of the photoeffect mechanism in the x-ray region[1,56,129-131] and study of the spatial and energy distributions of the photoelectrons.[150] In the study of exoelectron emission the existence of multipliers has permitted experiments to be conducted in vacuum and temperature-emission curves to be easily obtained.[14,63]

Multipliers have been used successfully in experiments on the passage of ions[151,152] and electrons through matter. Multipliers are used in scanning electron microscopes to detect scattered electrons and secondary electrons and to obtain a television picture of the surface being studied,[153,154] and also in electron diffraction with objective recording. In the latter case the electrons scattered from the sample under study are scanned with respect to the three entrance apertures of the multiplier, which form a filter for incoherently scattered electrons, and a chart recorder traces out an intensity distribution curve for the reflections of the electron diffraction pattern after subtraction of background.[156]

In addition, there are reports of use of blocks of channel multipliers to transform x radiation with quantum energies from 50 keV to 1 MeV into the visible region in x-ray defectoscopy,[52] and of multipliers with cathodes of a set of thin metallic foils to detect very hard electromagnetic radiation.[28]

The list of examples of the use of multipliers could be continued, but the list already presented and the data of the preceding chapters indicate the extremely broad possibilities of this device.

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