DETECTION OF ION BEAMS BY ELECTRON MULTIPLIERS IN MASS SPECTROMETRY AND NUCLEAR PHYSICS

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INTRODUCTION

IN recent years there has been an increasing use of mass spectrometry in the analysis of radioactive fuel products and in the search for traces of nuclides that are formed in nuclear reactions; in this connection the need has arisen for a very sensitive ion detector. The development of magnetless radio-frequency mass spectrometers requires simple ion detectors with no time delay. The use, in these applications, of the usual detection schemes, which use electrometers or vacuum-tube amplifiers, involves a number of difficulties when one wishes to detect ion currents smaller than 10^{-15} to 10^{-16} amp. It is more convenient to use electron multipliers as detectors; these multipliers have alloy cathodes with which it is possible to detect charged particle beams characterized by intensities of 10^{-19} amp and pulse lengths of approximately 10^{-9} sec. In nuclear physics these multipliers are frequently used for the detection of recoil nuclei with energies of several tens or hundreds of electron volts, that is to say, when the use of other types of counters is not feasible.

In the present article we review the transformation of the ion beam into an electron beam at the cathode of the multiplier, the efficiency of the multiplier for counting particles, and the gain stability of a multiplier. Various examples are considered, and certain features of the application of electron multipliers as ion detectors are considered in connection with mass spectrometry and nuclear physics. A great deal of important information concerning the characteristics and construction of electron multipliers can be found, for example, in Electron Multipliers by N. O. Chenka, S. M. Fainshtein and T. M. Lifshitz.

1. TRANSPORTATION OF AN ION BEAM INTO AN ELECTRON BEAM

A photograph of an electron multiplier with the cover removed is shown in Fig. 1. Multipliers of this type are used frequently for the detection of ion beams. The transformation of the ion beam into an electron beam takes place at the cathode of the multiplier as the result of the ejection of secondary electron ions. By definition the emission coefficient (γ) is the number of electrons emitted by the target divided by the number of heavy particles which strike the target in the same time period. The value of γ is a linear function of ion energy up to several kilo electron volts; the linear region of $\gamma(E)$ increases as the mass number of the bombarding ions increases.[1,2]

Figure 2 shows the output current of an electron multiplier used to detect different ions; the current is plotted as a function of ion energy, which is increased from 5 to 250 kev.[3] The masses of the detected ions vary from 1 to 40. The multiplier has 11 activated beryllium-copper dynodes. The gain of the multiplier is approximately 10^6. From the behavior of the curve shown in Fig. 2 it is apparent that the output current from the multiplier is higher over the entire energy range for high-mass ions when the ion energy is greater than 15 to 25 kev. On the other hand, at ion energies below 15 to 25 kev the light-ion current is higher. For a proton beam the maximum output current (the maximum value of γ) is observed at approximately 100 kev.[5] When the energy is increased beyond several hundred kilo electron volts, γ falls off slowly for protons and deuterons.[4-7]

As the mass of the bombarding ion increases the position of the maximum on the $\gamma(E)$ curve is shifted toward the high-energy region.[8,10] Thus, when He^+ ions bombard a molybdenum target whose surface is not atomically pure the maximum of the function $\gamma(E)$ is observed in the region from 200 to 400 kev.[8] On the average, one α particle ejects approximately 10 electrons from a metal;[9,10,27] this relation holds over a wide energy range.

Because of the increasing use of electron multipliers in mass spectrometry it is of considerable interest to know the dependence of γ on the mass of the ion, m_i; however, this relation had not been established until recently. Figure 3 shows a family of $\gamma(m_i)$ curves obtained by bombarding an activated target of silver manganese with ions of the

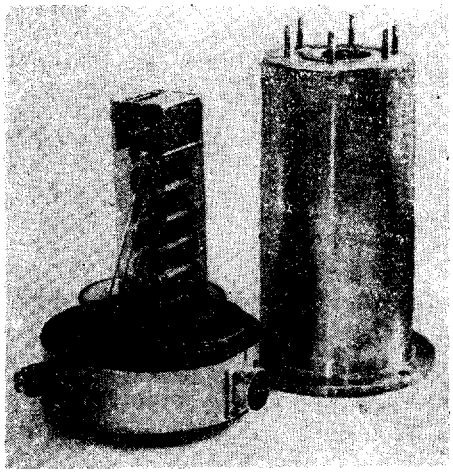

FIG. 1. Electron multiplier with the metal cover removed.

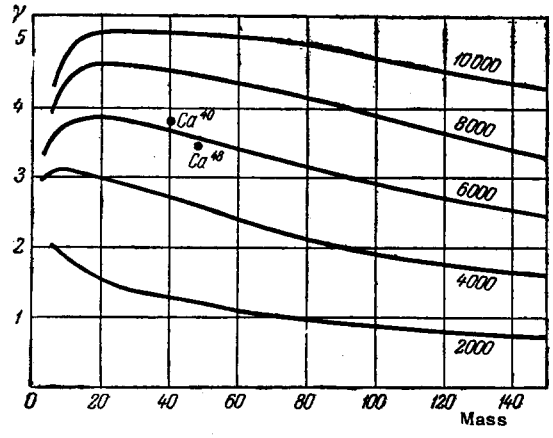

FIG. 3. Dependence of γ on ion mass for various values of the ion energy.

alkali metals at several values of ion energy.[2] At ion energies of approximately 2 kev, γ falls off with increasing ion mass. However, at ion energies of 8 to 10 kev there are sections on the $\gamma(m_i)$ curves where γ is more or less independent of ion mass. The same figure shows values of γ measured by bombarding targets with Ca^{40} and Ca^{48} ions with energies of 6 kev; it is apparent that $\gamma(m_i)$ varies more rapidly for ions of isotopes of the same element than for different elements. Apparently γ depends on the structure of the electron shells of the bombarding particles[1] as well as on the mass.

Ploch and Walcher[11-13] have investigated the function $\gamma(m_i)$ for the bombardment of Pt, Mo, Be, and Cu targets by the following positive ions: Li^6, Li^7, Ne^{20}, Ne^{22}, K^{40} and K^{41}; the surfaces of these targets were not atomically pure. These authors find that, as the ion energy is varied from 0.6 to 6 kev, ions of different isotopes (with the same velocity) eject the same number of secondary electrons.

It is found that molecular ions eject more electrons from metal targets than do atomic ions of the same energy, mass, and charge.[3,6,16] Figure 4 shows the output current of an electron multiplier with activated AgMg emitters (1.7% Mg) as a function of the mass and molecular structure of the detected ions.[1] The ion energy is 7 kev. The output current produced in detecting CH_2^+ ions is approximately 10% greater than that produced by atomic N^+ ions.

When targets are bombarded by molecular and atomic ions of higher mass, a considerable difference in the number of ejected electrons is observed. Thus, for example, 9-kev $C_{14}H_{10}^+$ ions eject approximately 2.2 times as many secondary electrons as do Hf_{178}^+ ions of the same energy;[15] these data refer to an electron multiplier with an activated beryllium-copper cathode.

The number of secondary electrons ejected from the metal depends on the magnitude and sign of the charge of the interacting particle. Negative ions give rise to more electrons than similar ions of positive charge;[1,17] neutral atoms produce approximately the same number of secondary electrons as singly-charged positive ions of the same energy.[18,19] A number of authors have observed that

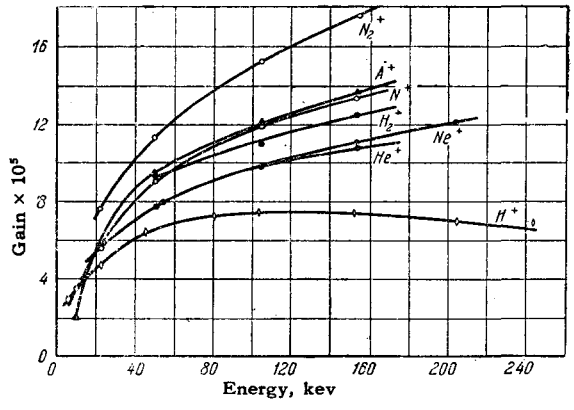

FIG. 2. Variation in output current of the multiplier as a function of ion energy for different ions.

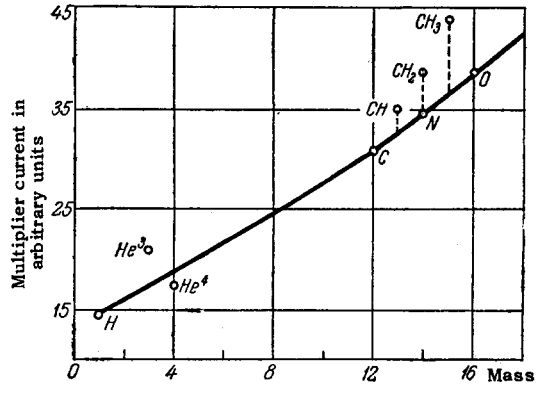

FIG. 4. Effect of the molecular configuration of the ion on the output current of the multiplier.

the value of γ increases as the charge of the positive ion increases.[20,22,23]

As the angle of incidence of the ion beam on the target increases the value of γ also increases.[1] For protons with energies of several hundred kev γ varies in proportion to the secant of the angle of incidence.[4,24]

The energy distribution of the secondary electrons is virtually unaffected by an increase in mass and energy of the bombarding ions. Most of the secondary electrons have energies below 30 ev.[8,21,22,24] The angular distribution of the secondary electrons is given roughly by the cosine law.[25]

2. COUNTING EFFICIENCY OF ELECTRON MULTIPLIERS FOR CHARGED PARTICLES

To determine the absolute intensity of an ion beam with an electron multiplier one must know the counting efficiency of the multiplier. In the ideal case each particle incident on the cathodes of the multiplier should give rise to a voltage pulse at the output; the amplitude of this pulse should be sufficient to ensure its being recorded by the counting circuit. However, since the electron emission due to the action of the bombarding particles is of statistical nature, there are always cases in which the incoming particle does not eject a secondary electron from the cathode. For this reason the counting efficiency of the electron multiplier is not exactly 100%.

The counting efficiency of a multiplier is usually determined by comparing the intensity of the particle beam incident on the cathode with the pulse counting rate in the counting circuit, as measured by means of an electrometer or a dc amplifier. In measurements of this kind the intensity of the particle beam is usually of the order of 10^{-15} amp (approximately 10^5 singly-charged particles per second); this guarantees a relatively small error when the ion beam is detected with an electrometer, dc amplifier, or counting circuit.

It has been shown experimentally[3] that H_1^+, H_2^+, He^+, Ne^+, M^+, A^+, and N_2^+ ions with energies from 10 to 200 kev are detected with an efficiency of $100^{+0\%}_{-5\%}$; these data refer to an 11-stage electron multiplier with an activated beryllium-copper emitter. In Fig. 5 the counting efficiency for N^+ ions is shown as a function of ion energy. The counting efficiency is 92% for an ion energy of 4 kev and almost 100% for ion energies between 10 and 200 kev. The reduction in counting efficiency for N^+ ions at 4 kev is apparently due to statistical fluctuations in γ. The mean value γ for bombardment of alloy emitters by N^+ ions with energies of 4 kev is approximately three.[1,2] If one assumes that the electron emission due to ions with energies of 4 kev has a Poisson distribution, the probability for events in which $\gamma = 0$ can be found from the expression $\beta_\gamma = (\bar{\gamma}^\gamma/\gamma!)\,e^{-\bar{\gamma}}$ where β_γ is the probability of ejection of γ secondary electrons by the ions. If $\gamma = 3$, then $\beta_{\gamma=0} \approx 0.05$ i.e., approximately 5% of the N^+ ions incident on the cathode do not eject secondary electrons.

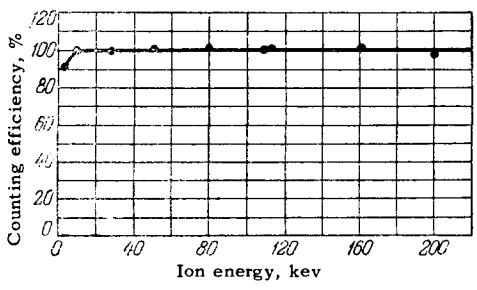

FIG. 5. Counting efficiency for N^+ ions as a function of energy.

In addition to the statistical fluctuations in γ, there is another effect that reduces the counting efficiency for 4-kev N^+ ions; this effect arises as the consequence of the wide amplitude distribution of the pulses from the multiplier. Some of the pulses are not recorded by the counting circuit because they are comparable in amplitude with the noise of the linear amplifier and lie below the amplitude threshold of the discriminator.

Morrish and Allen[26] have shown that electron multipliers with beryllium-copper emitters detect Li^+ ions with an efficiency of approximately 100% if the ion energy is greater than 2 kev. Allen[27] has noted that α particles with a wide energy distribution are detected by electron multipliers with an efficiency of about 100%. Neutral particles are detected with approximately the same efficiency as positive ions of the same energy.[3,28]

To obtain a high counting efficiency it is necessary that the sensitivity of the counting circuit be adjusted for the wide amplitude range of the pulses from the multiplier. The relative mean-square spread in M, the gain of an electron multiplier for ion detection, is given by the expression[27]

$$\frac{\overline{\Delta M^2}}{M^2} = \frac{\overline{\Delta\gamma^2}}{\gamma^2} + \frac{\overline{\Delta\sigma^2}}{\gamma\sigma(\sigma-1)}, \qquad (1)$$

where σ is the mean gain per stage of the multiplier.

Equation (1) can be simplified by assuming that the emission of electrons due to ion collisions follows a Poisson distribution, i.e., $\overline{\Delta\gamma^2} = \gamma$, while $\overline{\Delta\sigma^2}$ is approximately 2σ for primary electron energies of approximately 400 ev for a beryllium emitter.[29] Equation (1) then becomes:

$$\frac{\overline{\Delta M^2}}{M^2} \approx \frac{1}{\gamma}\left[1+\frac{2}{(\sigma-1)}\right]. \quad (2)$$

It follows from Eq. (2) that the relative mean-square spread M is inversely proportional to γ.

Electron multipliers with cathodes of large area are used for detecting wide ion beams or divergent ion beams. The counting efficiency for these multipliers also depends on the point of incidence on the cathode. Trebukhovskii et al.[31] describe a 15-stage electron multiplier with input-window dimensions 44×44 mm^2. The cathode and emitters of the multiplier are made of beryllium-copper. In this work the local characteristics of the multiplier were investigated by bombarding a cathode at a potential of approximately -5 kev with α particles from Po^{210}. It was found that the efficiency for counting α particles was reduced by edge effects at the cathode.

To obtain more uniform local characteristics the cathode of the multiplier must be kept at ground potential while the anode must be kept at a high positive potential. This mode of operation of the electron multiplier does not cause any significant reduction in the counting efficiency for ions if the initial ion energy is greater than several kev. When the initial energy of the ions is insufficient to cause detection by the electron multiplier, a high negative potential is applied to the cathode of the multiplier. In this case more uniform local characteristics can be obtained by using metal shields (which are kept at cathode potential) in the primary-electron region.

The counting efficiency for electrons and ions depends on the energy. The maximum electron counting efficiency is observed at electron energies of several hundred electron volts (Fig. 6);

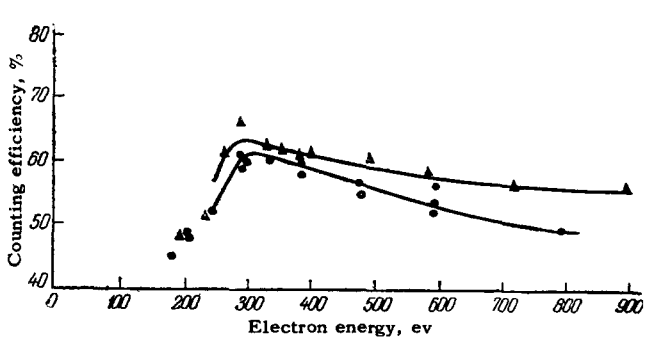

FIG. 6. Counting efficiency for N^+ ions as a function of energy. ▲) directly after activation of the multiplier, ●) after exposure of the multiplier to air for a period of five months.

this efficiency varies between 60 and 70%, depending on the degree of activation of the multiplier cathode.[32] According to the data reported by Allen[33] the counting efficiency for 500-ev electrons is almost 100%; at 6,000 ev this figure becomes 40%.

Electrons with energies of 30 kev are detected with an efficiency of approximately 23% by an RCA electron multiplier with beryllium-copper emitters. Beta particles with energies of 1 or 2 Mev are detected with efficiencies of several percent in electron multipliers.[34] The detection efficiency for electromagnetic radiation is several tenths of a percent.[35-36]

3. STABILITY OF MULTIPLIER GAIN

When electron multipliers are used in mass spectrometers or other physical research apparatus the electrodes are affected by various gases, ion bombardment, and so on. It is of interest to examine these effects, chiefly in connection with the gain stability of the electron multiplier.

Ion beams are most frequently detected by electron multipliers with beryllium-copper emitters which are relatively insensitive to exposure to air. After activation, a 12-stage electron multiplier of this kind was found to maintain a stable gain of the order of 10^6 for a period of several months even though air was allowed into the chamber.[30] Emitters of electron multipliers are also made from manganese alloys of copper, silver and aluminum;[1,36] however, these multipliers are more sensitive to air than those with emitters made from beryllium alloys.[38] To increase gain stability multipliers are sometimes made of unactivated beryllium-copper or of brass.[40] The gain of an 11-stage electron multiplier with slightly activated beryllium-copper emitters was approximately 10^5 for an interstage voltage of 400 volts.[3]

Fatigue effects are sometimes observed in the last emitters when intense ion beams are detected by electron multipliers; these effects cause a reduction in gain. Beryllium emitters are found more stable than magnesium in this respect.[38] Fatigue effects are observed in alloy emitters when the output current becomes somewhat greater than several milliamperes per square centimeter.

When several ion beams whose intensities differ by several orders of magnitude are detected by an electron multiplier within a short time period (for example, in using a mass-spectrometer to determine relative isotopic compositions) it is observed that the gain of the multiplier does not remain constant.[41] This instability is due primarily to charging of the insulators located near the trajectories of scattered electrons. To reduce this effect it is desirable to use an electrode system in which there is very little electron scattering and in which the number of insulators located near the trajectories is kept to a minimum. An electrode system of this type has been described in reference 42.

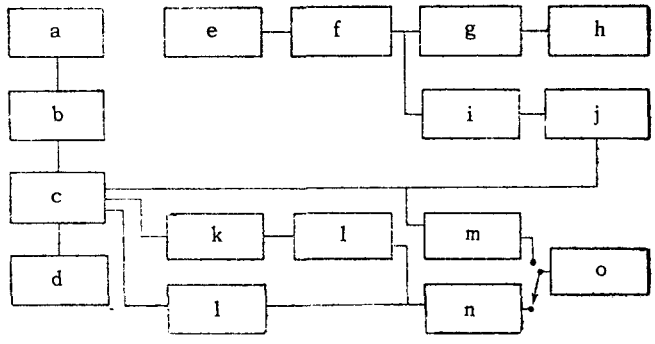

FIG. 7. Block diagram of the detection system in a mass spectrometer. a) Ion source; b) Fil. supply; c) Switch; d) Accel. volt. supply; e) 6,000-v power supply; f) Electron multiplier; g) Dynamic electrometer; h) Recorder; i) Preamplifier; j) Amplifier and discriminator; k) Scaler (10^2); l) Scaler (10^4); m) Integrator; n) Output meter; o) Recorder.

If the interstage voltages are low the gain stability is sensitive to variations in the voltage from the high-voltage power supply to the voltage divider. However, at interstage voltages of 500 to 600 volts the stability of the multiplier is much better.[3]

Transient discharges in multipliers reduce the gain by several percent.[3] If the discharge lasts for a minute or more the gain can be reduced by one or two orders of magnitude until the electrode system recovers. No change in multiplier gain is observed when the vacuum in the chamber deteriorates from 2×10^{-5} to 6×10^{-5} mm Hg.[3]

To obtain high stability the multiplier is generally mounted inside a metal chamber. In physical research electron multipliers are generally used as dc amplifiers or as particle counters. From the point of view of stability the latter type of operation is to be preferred. When a multiplier is used to count individual particles the threshold of the pulse-height discriminator can be set at a level such that the smallest particle-pulse exceeds the threshold by a wide margin (because of the small inherent background in the multiplier) so that these pulses are recorded in the counting circuit. A change in the gain of the multiplier shifts the pulse-amplitude spectrum; however, the pulse counting rate does not change because all pulses are above the discriminator threshold. When a multiplier is used as a dc amplifier, however, the amplifier output signal depends on the multiplier gain.

4. APPLICATION OF ELECTRON MULTIPLIERS IN MASS SPECTROMETERS

It is possible to increase the sensitivity of mass spectrometers by approximately 3 orders of magnitude when electron multipliers are used as detectors.

Figure 7 shows a block diagram of detection apparatus used in various forms for the detection of ion beams in mass spectrometers.[14,79] The multiplier used in reference 14 has 20 stages connected in an Allen arrangement. The emitters of the multipliers are made of slightly-activated beryllium copper, thus making the gain relatively insensitive to the effect of air. The gain of the multiplier is 3.6×10^7 (mean gain of 2.6 per stage). The anode of the multiplier is also connected to a dynamic electrometer (connected in turn to an automatic recorder) and to a pulse preamplifier with a gain of 10. The main pulse amplifier has a gain of 300. The pulses are fed from the amplifer to a scaler and then to an output meter and recorder. The switching system is arranged so that the output meter reads all pulses or every tenth, hundredth, or thousandth pulse. The pulse integrator is used to record pulses at very low repetition rates, when the output meter cannot be used. Ion currents of the order of 10^{-15} amp are recorded simultaneously by the electrometer and the counting circuit. At ion currents greater than 10^{-13} amp only the electrometer is used. In the detection system described here the counting losses are 0.1% for 82,000 pulses per minute and 1% for 820,000 pulses per minute.

When an electron multiplier is used as a particle counter it is possible to detect currents between 10^{-19} amp and 10^{-14} amp and to measure isotope ratios of the order of 10^5. It is also possible to measure higher isotope ratios when isotopes are present in amounts such that comparison measurements can be made.

To measure isotope ratios in a mass spectrometer in which the ion detector is an electron multiplier, it is necessary to take account of the dependence of output signal on the mass of the ion being

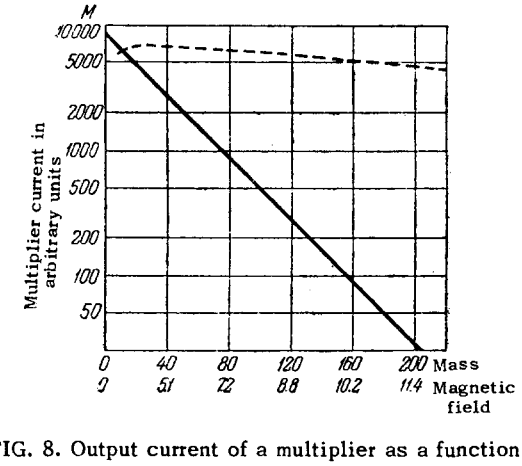

FIG. 8. Output current of a multiplier as a function of the fringing magnetic field and the mass of the detected ions (solid curve). The dashed curve is the calculated dependence of multiplier output current on ion mass when there is no magnetic field.

detected. At the present time, however, this question has still not been settled. Ploch and Walcher[13] propose that when the electron multiplier is used as a dc amplifier the following correction must be introduced for the ion mass in order to determine the true isotope ratio R_{true}:

$$R_{true} = R_{meas}\left(1 + q\frac{M_r - M_a}{M_a}\right),$$

where R_{meas} is the measured isotope ratio

$$q = \left(\frac{\partial \gamma_a}{\partial u}\right)_{M_a} : \left(\frac{u_0}{\gamma_a(u_0)}\right),$$

u is the ion accelerating voltage, u_0 is the ion accelerating voltage during the measurement, M_a and M_r are respectively the masses of the abundant and rare isotopes $\gamma_a(u_0)$ is the value of γ when the cathode is bombarded by ions of the abundant isotope accelerated by the voltage u_0. The quantity q can be determined by measuring i_0, the output current of the multiplier when the abundant isotope is detected at an accelerating voltage u_0, and $i_0 + di_0$, the current when the voltage is changed by an amount du. We find that $q = di/i_0 : du/u_0$. The quantity q depends on the state of the cathode surface and on the ion energy and varies from 1 to $\frac{1}{3}$.

The need for introducing corrections when determining isotope ratios by a mass spectrometer in which an electron multiplier is used has been indicated by a number of authors.[1,2,92] At the same time, White and Collins[14,46] and Andreeva[79] report no distortion in the isotope ratios when detecting ions with electron multipliers. The same is reported by Leland[45] and Kennett and Thode,[81,92] who used an electron-multiplier mass spectrometer to investigate the rare gases formed by fission of U^{232}, U^{235}, and Pu^{239}.

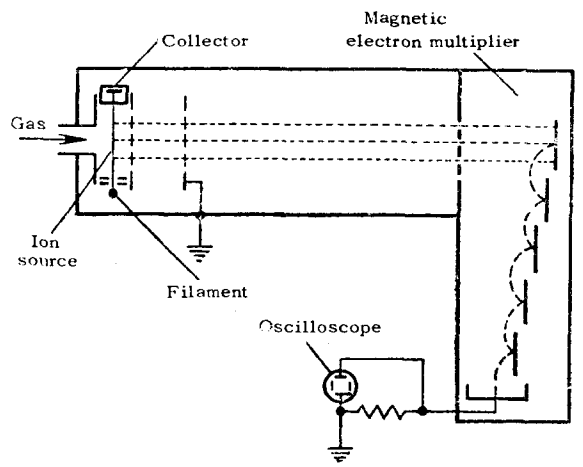

FIG. 9. Diagram of a radio-frequency mass spectrometer with a magnetic electron multiplier.

The use of an electron multiplier as a particle counter for individual ions yields a significant reduction in the difference between the measured and true isotopic ratios. When ions of the different isotopes are detected there is a change in the mean amplitude of the multiplier pulses. However, since there is a pulse-height discriminator at the output of the amplifier, and since this unit produces a standard signal regardless of the amplitude of the input pulses, the counting rate remains unchanged if the discriminator threshold is set below the level of the smallest pulses. On the other hand, when the energy of the detected ions is less than 10 kev, as is usually the case in mass spectrometers, the ion counting efficiency may be different for different isotopes, since ions of different isotopes eject different numbers of secondary electrons from the multiplier cathode.

In considering the use of a multiplier in a mass spectrometer one must keep also in mind the fact that the magnetic fringing field of the spectrometer can have a strong effect on the operation of the electron multiplier, causing defocusing of the electron beam. If there is a very strong fringing field the multiplier may be completely inoperative. Figure 8 shows curves for γ at the cathode of the multiplier (dotted curve) and the gain of the multiplier (solid curve) as functions of the mass of the ion being detected and the strength of the spectrometer fringing field.[1] The difference between the two curves is a result of the reduction in multiplier gain as the strength of the fringing field is increased. Two methods are used to compensate for this effect. In one case the electron multiplier is placed in a magnetic shield. In the second case an auxiliary magnet is placed near the multiplier in such a way as to set up a field which compensates for the fringing field of the mass spectrometer.

Special magnetic electron multipliers have been devised for operation in uniform magnetic fields up to several hundred oersteds.[43]

Because of their high resolving power electron multipliers are widely used in magnetless radio-frequency mass spectrometers; with these instruments it is possible to examine the mass spectrum of any material in a short period of time. The spectrum is observed on the screen of an oscilloscope. The multipliers in these instruments are pulsed and detect ion bunches corresponding to pulse lengths of tenths of a microsecond.[39,47-49]

Figure 9 shows a diagram of a magnetless, radio-frequency mass spectrometer in which a magnetic electron multiplier is used.[48] The cathode in this multiplier is a plane surface; with this ge-

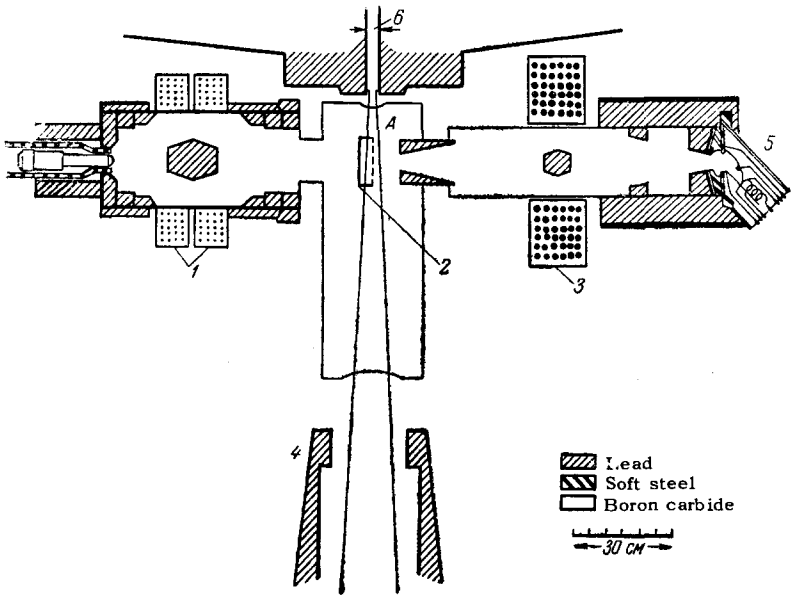

FIG. 10. Apparatus for the investigation of β decay of the neutron. 1) Electron spectrometer; 2) semi-cylindrical electrode; 3) proton spectrometer; 4) beam collector; 5) electron multiplier; 6) cross-section of the neutron beam.

ometry one can minimize effects which tend to increase the duration of the multiplier pulse Δt_i because of the non-simultaneous arrival of ions at the cathode of the multiplier. This is to be contrasted with other multiplier systems in which curved cathodes are used. Thus, for example, in a standard electron multiplier with trough-shaped electrodes we find that with a cathode potential of -4 kev and ions of mass 100, $\Delta t_i \approx 5 \times 10^{-8}$ sec.[50] In the case of an electron multiplier with "venetian blind" electrodes we find $\Delta t_i \approx 2 \times 10^{-8}$ sec under the same conditions.[50] The computed length of the pulse from a magnetic electron multiplier is 1.3×10^{-10} seconds;[43] this value is considerably smaller than that in electron multipliers with focusing electrodes. For this reason, it is possible to use in magnetic electron multipliers a large number of emitters of non-activated beryllium-copper with an average gain per stage of the order of two. The gain of such a multiplier is not affected if the electrodes are exposed to air or to various gases. The magnetic electron multipliers used in mass spectrometry have varying numbers of stages and overall gains ranging from 10^5 to 5×10^9. The pulses from multipliers with high gains are applied directly to the plates of a cathode-ray tube.

In the analysis of mass spectrograms it is necessary to take account of the fact that the output signal from the electron multiplier is different for different ions. To obtain precise values in mass analysis it is necessary to calibrate the mass spectrometer with a gas of known composition.[51]

Magnetic electron multipliers are also used for detecting ions in dynamic mass spectrometers such as the chronotron.[52] A basic disadvantage of magnetic multipliers is the fact that these devices require a uniform magnetic field of several hundred oersteds.

Electrostatic electron multipliers are also of interest. A recently developed electron multiplier in an image converter[53] is characterized by an extremely short pulse. An experimental version of this device has been constructed in the form of a demountable photo-multiplier; however this multiplier can be used for ion detection when the photocathode is replaced by an emitter which emits electrons directly when struck by charged particles. Amplification of the electron flow in the multiplier is achieved by secondary emission from the "back" of thin film emitters. The measured rise time for pulses in the multiplier is 1×10^{-9} sec; according to the design calculations this time should be of the order of 10^{-11} sec. The high resolution is obtained by means of the high interstage voltages and simple geometry.

Electron multipliers have also been used successfully for detecting ions in radio-spectroscopy devices in the determination of magnetic moments of different isotopes contained in a mixture of isotopes.[54-57]

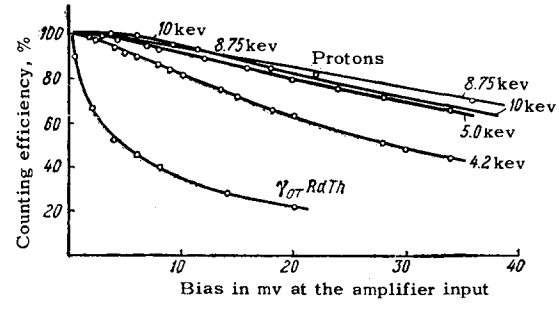

FIG. 11. Discrimator curves for the detection of protons and γ rays by an electron multiplier.

5. APPLICATION OF ELECTRON MULTIPLIERS IN NUCLEAR PHYSICS

The experimental study of different β transformations requires that one detect recoil nuclei with an initial energy of several tens or hundreds of electron volts. Electron multipliers turn out to be the most convenient detectors for such slow ions. In particular, electron multipliers have been used successfully in studying the β decay of the free neutron.[58-60] A diagram of the apparatus used in a number of investigations of β-decay of free neutrons[58] is shown in Fig. 10. The recoil protons formed in the neutron beam are focused from region A into the input window of a proton spectrometer; a positive potential of approximately 10 to 15 kv is applied to the semi-cylindrical electrode in the spectrometer. At the output of the proton spectrometer there is a beryllium-copper electron multiplier which detects the recoil protons. The electrons formed in the β decay of the neutrons are detected by a scintillation counter. The pulses from both counters are applied to a coincidence circuit. The background of this experiment is very large because of the scattered γ radiation. Figure 11 shows discriminator curves obtained by using an electron multiplier with beryllium-copper emitters; these data pertain to protons with energies ranging from 4 to 10 kev and γ rays from Ra-Th.[35] From the behavior of these curves it is apparent that wide amplitude ranges are obtained when a multiplier is used to detect protons and γ rays. Although an amplitude discriminator can be used in helping to distinguish the proton pulses from the γ background this procedure leads to a considerable reduction in the proton counting efficiency.

Electron multipliers have been used widely in detecting recoil nuclei formed in β transformations of various radioactive isotopes. The most convenient examples are the radioactive isotopes He^6, Be^7, Ne^{19}, A^{37}.[61-70] The energy of the recoil nuclei in different experiments has been measured by means of an electrostatic spectrometer or spectrometers in which measurements are made of the time of flight of the recoil proton from the source to the cathode of the electron multiplier. When electron multipliers are used in these experiments in cases in which the cathode of the electron multiplier is in line with the source of recoil nuclei, the multiplier background increases significantly when the source is heated. This is apparently due to detection of ions formed at the surface of the heated target. In another case[62] it has been noted that when an electron multiplier is used to record Li^+ recoil nuclei the multiplier background during the measurements varies from 4 to 40 pulses per minute; this is apparently due to the increase in thermal emission from the cathode of the multiplier as a consequence of the deposition of a lithium layer. According to quantitative estimates of the number of recoil nuclei incident on the cathode of the multiplier, it is necessary to make corrections because some of the recoil nuclei are intercepted by a grid which is generally used to obtain a more uniform electric field in front of the input window of the multiplier. In addition, it is necessary to take account of the fact that the different recoil nuclei are charged and that the efficiency of the counter may also depend on the charge of these nuclei.

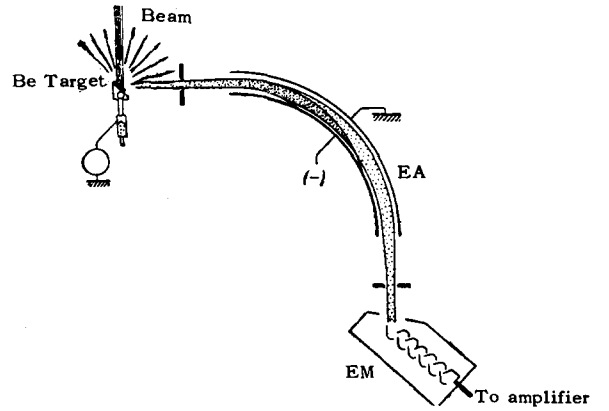

FIG. 12. Apparatus used to investigate the energy spectra of nuclear reaction products. EA) electrostatic analyzer, EM) electron multiplier.

In a number of cases electron multipliers have been used for detection of heavy charged particles which are produced in nuclear reactions caused by the bombardment of a target by a beam of accelerated ions.[71-73] Figure 12 shows a diagram of an experiment carried out by del Rossario[71] to determine the energy of products of nuclear reactions produced in the bombardment of a beryllium target by protons with energies of 239, 268, and 397 kev. The energy of the charged particles formed in the $Be^9(p,\alpha)Li^6$ and $Be^9(p,n)Be^8$ was determined by means of cylindrical electrostatic analyzer. The electron multiplier was used to detect particles which passed through the analyzer. The multiplier had 12 beryllium-copper dynodes. The energy spectra of the lithium ions formed in these nuclear reactions are shown in Fig. 13. The high counting rate in the low-energy region is due to the scattered protons; because of this background it was impossible to determine the position of the Li^{+3} peak for bombardment by 397-kev protons.

Tulinov[73] investigated the angular distribution

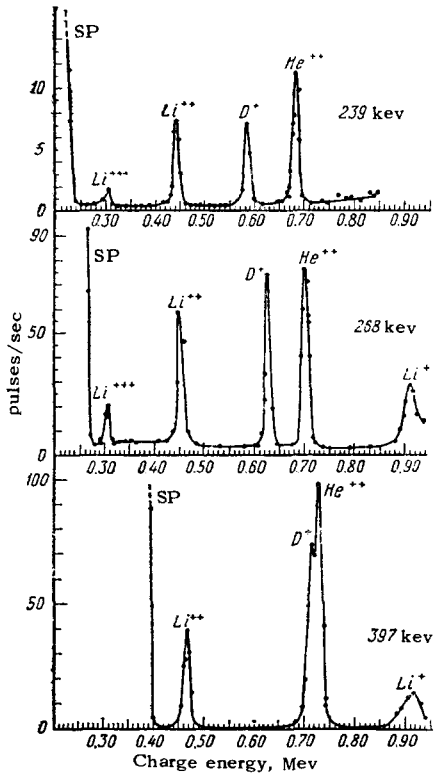

FIG. 13. Energy spectra of charged particles produced in nuclear reactions induced by protons with energies of 33, 239, 268, and 397 kev. SP) scattered proton.

of recoil nuclei from the $Be^9(d, \alpha)Li^7$ reaction; it was found possible to use the angle method to study the energy levels of the recoil nuclei. In this experiment a beam of deuterons accelerated to approximately 4 Mev in a cyclotron passes into the experimental chamber and bombards a beryllium target. The α particles formed in the nuclear reactions are detected with a proportional counter and the Li^7 recoil nuclei, with energies of approximately 1 Mev, are recorded by an electron multiplier with beryllium-copper emitters. The pulses from both counters are applied to a coincidence circuit. During the measurements it was found that the background loading of the multiplier was very large, so that it was difficult to obtain precise data. When thin organic films, through which the recoil nuclei could pass easily, are placed in front of the input window of the multiplier the background is reduced substantially.

Apparently the high background when there is no organic film in front of the input window results from the detection of slow ions or ultraviolet photons produced as the deuteron beam passes through the target and working volume of the experimental chamber.

In certain experiments it is necessary to detect slow ions against a background of intense electromagnetic or particle radiation. In these cases the desired radiation can be separated by two-channel electron multipliers connected in coincidence or anti-coincidence.[74,75] In addition to being used in nuclear physics, electron multipliers have also been used in the investigation of the effects that arise in the passage of low-energy ions through matter.[76,77] In a number of investigations multipliers have been used to detect the neutral component of an ion beam which is formed when the ions pass through metal foils[28] or a gaseous medium.[78]

Electron multipliers with alloy emitters are characterized by high sensitivity to ions. In addition, these devices are relatively insensitive to exposure to air. For this reason it is possible that they will find application in the detection of weak ion currents in ionization gauges, for example in the high-vacuum radioactive ionization gauge described in reference 80.

We have not considered other applications of electron multipliers since these applications lie beyond the scope of the present review. However, we may mention the fact that multipliers with alloy emitters have also been used in the detection of electron beams in raster electron microscopes,[86] in secondary-emission vacuum tubes,[87,88] in television transmitting tubes, in studying the emission of electrons after mechanical processing of metal surfaces,[89] and so on. In addition, these multipliers find wide application in the detection of ultraviolet and soft x-rays.[36,90,91]

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