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A low background-rate detector for 40 keV ions using a conversion dynode and a microchannel-plate electron multiplier to reject low-energy ions, electrons, and photons

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We have developed and tested an inexpensive ion detector with dark-count rates below 10^{-4} s^{-1} and excellent background rejection. Each 40 keV ion that strikes a grazing-incidence Al_2O_3 conversion dynode ejects a few tens of secondary electrons, which enter separate pores of a microchannel plate and are independently multiplied to saturated pulse height. The pulses are summed to produce an output signal that is proportional to the number of secondary electrons. This permits pulse-height discrimination against backgrounds of low-energy ions, electrons, and photons. We have successfully tested the detector with C^+ , Na^+ , K^+ , Rb^+ , and Cs^+ at 5–40 keV, and with 36 keV C^- and CH^- . It should detect ions and neutrals of all species, at energies above 5–10 keV, with good efficiency and excellent background discrimination. Counting efficiency and background discrimination improve with higher ion energy. The detector can be operated at pressures up to at least 2×10^{-7} Torr and be exposed to air repeatedly without requiring reactivation. The maximum ion count rate is $3 \times 10^6 \text{ s}^{-1}$ in pulse counting mode and $6 \times 10^9 \text{ s}^{-1}$ in current integrating mode. Detection of 40 keV ions at rates below 10^{-2} s^{-1} was required in development of a 10 cm radius 40 keV cyclotron dedicated to high-sensitivity radioisotope dating by accelerator mass spectrometry (AMS). In the cyclotron, the detector suppresses to $6 \times 10^{-4} \text{ s}^{-1}$ the background-count rate from the presence of large numbers of low-energy ions, photons, and electrons.

INTRODUCTION

The application of high-sensitivity accelerator mass spectrometry (AMS) to radioisotope dating by direct detection of radioisotope atoms has made it possible to date much smaller samples than can be dated by decay-counting methods.^{1,2,3} The technique has greatly increased the number of samples that it is technically feasible to date. However, the expense and availability of accelerator facilities limit the number of samples that can be dated. To overcome this limitation we are developing a 10 cm radius, 40 keV

cyclotron^{4,5} for AMS radioisotope dating with the object of dating samples inexpensively and conveniently. We are initially developing the cyclotron for ^{14}C dating but modifications and different sources should allow the same machine to date samples using ^{10}Be and other isotopes.

AMS is typically applied to samples where the small number of long-lived isotope atoms available to count is the limiting factor. In all samples however, background molecules and isotopes of the same and nearby mass number are present at abundances many orders of magnitude higher than the trace isotope. Thus AMS requires a detection system that is sensitive enough to detect reliably a small number of accelerated trace isotope ions while discriminating against large numbers of background ions.

We have designed and built an ion detector⁶ to meet the requirements of low-background rate detection of 40 keV ions in the cyclotron. This detector combines the background-discrimination capability of a high-yield conversion dynode with the air compatibility and narrow pulse-height distribution of a saturated microchannel-plate electron multiplier. The detector is generally useful for detecting ions above 5 keV in applications requiring low count rates or background suppression. The detector is also useful in mass spectrometry because its response is insensitive to beam position.

This paper describes the design, performance, and operating ranges of the detector. We tested the detector in a well-understood mass spectrometer both to calibrate it for use in the cyclotron and to test the effects of changing various parameters, including detector voltages and ion species, energy, and incidence angle for more general use. The mass spectrometer was built previously by one of the authors, MCM. It is a single-direction focusing mass separator with a 1.5 m radius, 90° magnetic-sector analyzer and an oven-type source. We tested the detector over a wide range of operating parameters with positive and negative ions of various species, ^{12}C through ^{133}Cs , at 5 keV through 40 keV to learn information relevant to other possible applications. Higher energies allow higher counting efficiencies and lower backgrounds. In the operating 40 keV cyclotron the detector suppressed the background to below the design goal of 10^{-3} s^{-1} .

I. ION-DETECTION REQUIREMENTS

In the cyclotron we want to count ^{14}C ions at rates of on the order of 10^{-2} s^{-1} . In order to subtract reliably the background the detector should have a background rate below 10^{-3} s^{-1} . The detector is located in the cyclotron pressure vessel, 30 cm from the center of the cyclotron. For ^{14}C detection the obvious backgrounds requiring discrimination are

^{13}CH and $^{12}\text{CH}_2$ ions that are partially accelerated, scattered by residual gas molecules, and reach the detector with less than about 2 keV. Since the ^{13}CH and $^{12}\text{CH}_2$ are 10^8 – 10^{11} times more abundant than ^{14}C , the detector must be able to distinguish between 36 keV ^{14}C and the other ions which will reach it with energies of a few keV or less. However, since the cyclotron selects for mass and energy, it is not necessary that the detector discriminate between ions on the basis of mass or of a small difference in energy. In addition to low-energy background ions the cyclotron produces a large number of electrons, UV, and soft x rays, some of which reach the detector, and electronic noise from high-voltage discharge and radio-frequency pickup. These too must be distinguished from 36 keV ^{14}C ions. Use in the cyclotron during development requires that the detector operate at 10^{-7} – 10^{-6} Torr and withstand frequent exposures to air.

A. Limitations of other detectors

Previous accelerators used for dating have had energies in the 5–50 MeV range allowing the use of range and dE/dx methods of particle identification to eliminate background ions. The range of 36 keV ^{14}C ions from our low-energy cyclotron is only ~ 100 – 1000 Å in solids,⁷⁻⁹ so these methods are not currently possible. None of the detectors commonly used to detect 5–50 keV ions meet the cyclotron design requirements. Faraday cups cannot count individual ions. Detectors that use discrete-dynode electron multipliers require reactivation after exposure to air, and their dark-count rate is too high. Adding a high-yield first-stage dynode for conversion of the ion to secondary electrons does allow discrimination of much dark noise and background. However, the lowest dark-noise rate achieved¹⁰⁻¹² is still about 10^{-2} s^{-1} . The background rate in the cyclotron environment would be much higher. In Daly, or doorknob, detectors^{13,14} ions are post-accelerated, so ions of widely varying energies generate pulses of the same size. Channel electron multipliers and microchannel plates are often used as ion detectors. They may be exposed to air without requiring reactivation. However, they too produce output signals that are the same size for electrons, photons, and background ions as for higher energy ions. Solid-state detectors have background and dark-noise rates that are too high even when cooled to liquid nitrogen temperature. Their small output pulses make them particularly susceptible to the electronic noise generated by a cyclotron. Also, the thinnest surface barrier (the metal electrode through which radiation enters the detector) available in state-of-the-art detectors is a few hundred Å, comparable to the range of a 36 keV carbon ion.

II. DESIGN

A. Theory of operation

The purpose of the detector described below is to generate a large signal pulse in response to a 40 keV ion while keeping the rate of large dark-noise and background pulses as low as possible. A discrimination threshold can be set to accept the large pulses from 36 keV ions while rejecting the smaller pulses from the various background sources. The detector uses a two-stage amplification scheme. In the first stage, the conversion dynode preamplifies the ion signal by emitting more secondary electrons when higher-energy ions hit it. The dynode emits few secondary electrons in response to background ions, photons, and electrons. In the second stage the microchannel plate independently multiplies each secondary electron by about 10^7 . The anode collects the total charge, which is proportional to the number of secondary electrons emitted by the dynode. The total charge arrives at the anode within the time constant of the amplifier and discrimination electronics so the ion signal is detected as a single large pulse.

The detector gives proportional output for two reasons. First, the dynode emits tens of electrons with a few eV of transverse energy. They move away from each other as they drift toward the microchannel plate. Second, the holes, or pores, through the microchannel plate form a two-dimensional array of thousands of independent electron multipliers, each of which produces a fixed-size pulse when fired by an electron from the dynode.

In contrast to signal ions, dark noise and background usually cause no more than a single secondary electron to reach the microchannel plate and fire a single pore. Nonetheless, for reasons discussed in Sec. III.D, there is a low rate of background pulses above any given pulse-height threshold. Our design attempts to achieve consistently large signal pulses in order to allow use of the highest possible discrimination threshold for any given beam-ion counting efficiency. A higher threshold reduces the rate of dark-noise and background pulses that will be counted.

B. Mechanical description of detector

The detector (Figs. 1 and 2) consists of two parallel electrodes, 35×47 mm, with a drift field in the gap between. One electrode holds the dynode and the other holds the microchannel plate (Sec. II.F). The $13 \times 19 \times 3$ mm dynode (Sec. II.D) is made of flat, polished aluminum. It is dovetailed into a slot at the center of the dynode holder and may be easily replaced.⁶ The dynode holder mechanically supports the rest of the detector by a 10 mm-thick glass-ceramic insulating standoff connected to the electron-multiplier holder.

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Fig. 1 Schematic drawing of the detector. An ion beam (positive ions shown) hits the Al_2O_3 conversion dynode at grazing incidence. Each ion ejects a few tens of secondary electrons with a few eV of transverse energy. The electrons move away from one another as they are accelerated through 1 kV across the 1 cm drift gap toward the microchannel-plate face. Each electron triggers an avalanche in a separate microchannel-plate pore. This independently multiplies each electron by a factor of $\sim 10^7$ electrons. The anode collects the total charge.

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Fig. 2 The detector with the electron multiplier in its proper orientation, but before removal from the glass-and-metal vacuum vessel in which it was delivered. The replaceable dynode has been removed from its dovetail slot. To the left of the dynode holder is the cradle used during tests in the mass spectrometer to adjust the orientation of the detector for different ion-incidence angles. A different mount is used to hold the detector in the cyclotron.

Directly opposite the dynode, the electron-multiplier holder has a similar-size hole through which secondary electrons approach the microchannel plate. Ten gold-coated tungsten field wires, 25 μ in diameter, span this hole. In the prototype detector a sliding door is provided to cover the hole when the detector is out of vacuum to protect the microchannel plate from dust. The microchannel plate proved to be quite robust and the sliding door turned out to be unnecessary.

C. Ion-beam paths in drift gap

The first-order (parabolic) ion-beam paths in the constant electric field of the drift gap are easily calculated. These paths are independent of mass for beams of a given energy and charge. Thus there is no need to readjust the angle of the detector when sweeping from one mass to another in either the cyclotron or a conventional mass spectrometer.

In addition to generating larger signals for ions with more energy, the detector has a limited ability to prevent any signal at all from ions with energies that are grossly different from the energy required for an ion to hit the center of the dynode. Because the paths of ions with different energies curve differently in the drift field, they will undershoot or overshoot the dynode, depending on whether they are positive or negative and have more or less energy than the ions to be counted.⁶ This deflection is particularly effective for collimated backgrounds of charged particles with less energy than the beam. We calculate that for a 40 keV collimated beam aimed at the center of the dynode with an impact angle of 80°, positive ions entering the detector with an energy below about 10 keV in the same collimated beam would not reach the dynode. For ions that hit further than about 1 mm from the dynode, none of the secondary electrons can pass through the hole in the electron-multiplier holder to reach the microchannel-plate stack. These ions do not cause an electron multiplier pulse. Ions that miss the dynode create few secondary electrons because the surrounding aluminum is not polished. In the cyclotron the background has much lower energy than the beam but it is not well collimated. We made no controlled test of the extent to which the drift gap reduces the rate of small pulses from background ions and electrons that reach the dynode and microchannel plate.

D. Grazing-incidence conversion dynode and secondary-electron emission

The function of the conversion dynode is to emit as many secondary electrons as possible for each beam ion. Dietz suggested¹⁵ we use an aluminum oxide (Al_2O_3) dynode surface because it has a high secondary-electron yield, needs no activation, and is unaffected by exposure to air.^{16,17} The dynode will detect positive, negative, and neutral

atoms and molecules. Negative ions have a slightly higher secondary-electron yield due to the presence of the additional electrons.¹⁰ The yield of a molecular ion is typically comparable to the sum of the yields of its constituent atoms at the same velocity.¹⁸ Following Dietz's early method,¹² we used 1100-0 aluminum (formerly designated 2S), which is specified to be 99.0% pure. We prepared the conversion surface by sanding with 600 grit sandpaper, and polishing in a magnesium-oxide powder and water slurry containing 2% nitric acid and 1% hydrofluoric acid. We found that aluminum-oxide powder, which Dietz used in his slurry, tended to scratch the dynode. We substituted magnesium oxide, which better matches the hardness of aluminum. We then allowed the surface to oxidize in air (for over a year, as it happened). Before assembling the detector we cleaned the dynode and other parts (except for the electron multiplier) in an ultrasonic cleaner, first with 1,1,1 trichloroethane, then ethyl alcohol. On visual inspection the dynode we used is almost mirror smooth.

The dynode is oriented at grazing incidence to the beam to take advantage of the well-known secant dependence of secondary-electron yield on ion incidence angle from normal. This dependence arises because the secondary electrons have an escape depth of about 10 Å. The number of electrons that escape depends on the portion of the ion path length that remains within 10 Å of the surface. Several authors have seen this approximate secant dependence experimentally.¹⁹

Previous experimental data¹⁸ have shown that surfaces emit secondary electrons with a solid-angle density distribution approximately proportional to the cosine of the angle between their direction of motion and normal. The typical energy distribution of emitted secondary electrons has a peak at between 0 and 2 eV, and a median below 5 eV.^{18,20} The position of the mean and the length of the tail both decrease with increasing atomic number for incident alkali metal ions, Li, Na, K, Rb, and Cs. The energy distribution is insensitive both to the nature of the target and to ion energy up to several tens of keV.²¹

E. Separation between incident electrons at microchannel-plate face

It is important that the detector's output be proportional to the number of electrons incident on the microchannel-plate face. This allows discrimination between the signal from a full-energy ion, in which tens of electrons from the dynode hit the microchannel plate, and dark noise or background pulses, in which only a few electrons hit the microchannel plate. In the saturated, pulse-counting mode, the output of each pore is independent of how many electrons fire that pore simultaneously. The incident electrons

must land in well-separated pores for the electron multiplier to have the linear amplification required for proportional output. This ensures that they are independently multiplied and that the output pulse height, which equals the sum of the outputs of the fired pores, is proportional to the number of incident electrons.

An electron incident on the front face of the Z-stack fires a group of 7 pores in the output plate (Sec. II.F). As a result, a minimum separation of 3 pores between adjacent incident electrons is required. In practice a larger (but unknown) separation is required to ensure that each pore saturates completely since charge is conducted from neighboring pores.

Below we derive the average separation d between adjacent electrons as they hit the microchannel plate. Consider N secondary electrons emitted in a cosine angular distribution, each with initial energy E_o . In the center-of-mass frame of the electrons (which accelerates through the drift gap) they move away from one another in a small expanding hemisphere with a radius that remains much smaller than the drift gap. When the electrons reach the microchannel-plate face the hemisphere is projected into a disc. The secant factor that arises from the projection cancels the initial cosine angular distribution, so the electrons are distributed uniformly over a disc on the microchannel-plate face. The radius R of the disc is given by the product of the 1.4 ns time of flight and the magnitude of the initial velocity.

$$R = (t+t') v_o = \left(s \sqrt{\frac{2m}{e V_d}} + s' \sqrt{\frac{m}{2e V_d}} \right) \sqrt{\frac{2E_o}{m}} = (2s+s') \sqrt{\frac{E_o}{e V_d}}, \quad (1)$$

where v_o is the initial velocity, t is the time to cross the distance s (10.0 mm) from the dynode to the field wires, t' is the time to cross the distance s' (6.0 mm) from the field wires to the front face of the microchannel-plate, e is the electron charge, and V_d is the voltage between the dynode and the field wires (1 kV). The average spacing between adjacent electrons is $d = 2 (R^2/N)^{1/2}$, so,

$$d = 2(2s+s') \sqrt{\frac{E_o}{eNV_d}}. \quad (2)$$

As a conservative example we consider 30 secondary electrons emitted from the dynode with only 1 eV. (A typical range is 15–30 secondary electrons emitted with a few eV, and electrostatic repulsion between the electrons increases the energy to ~10 eV.) Then $R = 830 \mu$, and $d = 300 \mu$, so the separation is 20 pores since the pore spacing is

15 μ . This calculated mean electron separation is much greater than the minimum required separation of 3 pores. We did not test whether the actual separation was in fact sufficient to ensure that the output was proportional, but nothing in our data indicated that it was not.

Although d must be large enough for independent multiplication, if R is too large some of the secondary electrons will miss the hole in the electron-multiplier holder and not reach the microchannel plate. For an ion that hits the dynode more than 1 mm from any edge, fewer than ~25% of the secondary electrons will be lost.

F. Microchannel-plate electron multiplier

A microchannel plate is a disk of high-resistivity semiconducting glass, pierced by many tiny pores, each of which is a continuous-dynode electron multiplier.²²⁻²⁴ On each side of the disk the remaining web of glass is covered by a metal electrode used to apply a voltage. For our purposes, the important feature of a microchannel plate is its ability to multiply independently electrons incident on different pores. Although nearby pores are temporarily affected and give up some of their stored charge, the rest of the plate is available for simultaneous, independent multiplication of other incident electrons.

This detector employs the electron multiplier used in the ITT F4129 Z-stack microchannel-plate phototube.²⁵ This multiplier consists of three microchannel plates, an anode, and a guard ring in a ceramic and glass housing (Fig. 1). The microchannel plates are stacked with no spaces between them and alternating 5° bias angles on the pores of each plate to prevent ion feedback. A pore fired in the input plate typically fires 3 adjacent pores in the middle plate and 6–7 in the output plate. Each plate contains 1.3 million pores, 12.5 μ in diameter and 15 μ on center, within its 18 mm diameter active area. The upper limit on the number of independent electron multipliers is the total number of pores in one microchannel plate divided by the 6.5 pores typically fired in the output plate, or about 2×10^5 . Eberhardt has provided an extensive list of values for parameters of the F4129 multiplier.²⁶

We operate the electron multiplier in the pulse-counting mode, in which the voltage across the plates is high enough that the pulse height saturates, limiting the output charge.^{22,24,27} Saturation occurs in a pore when the number of electrons in an avalanche becomes large enough to leave a deficit of charge on the pore walls behind it. This reduces the local electric field and thereby reduces the impact energy of electrons in the avalanche, which lowers the average gain per collision asymptotically to unity. Thus for a given voltage across the microchannel-plate stack the output is about the same size each time a

pore in the input plate is fired.

The wall thickness between pores is $2.5\text{ }\mu$ at its narrowest. This is a typical range for ions with energies up to a few MeV²⁸ and electrons or photons with energies up to a few keV.²⁹ At lower energies, ions, electrons, or photons hitting the microchannel plate directly will fire only one pore in the input plate. Thus the background pulses they generate will be about the same size as those from a single incident electron.

The electron multiplier collection efficiency is defined as the probability that an electron that hits the microchannel plate will fire a pore and be multiplied. For the F4129 electron multiplier the manufacturer claims that the collection efficiency for electrons with greater than 200 eV is between 60% and 100% and quotes 85% as the nominal collection efficiency.³⁰ Measurements on other microchannel plates yield collection efficiencies of about 90%, even for electron energies as low as 100 eV.³¹ Over the surface of the microchannel plate the collection efficiency varies less than 1% on scales of $10\text{ }\mu$ to 1 mm (consistent with statistical fluctuations in the measurement).^{32,33} There are variations of 5–10% over scales larger than 5 mm.³⁴

G. Electronics

The detector dynode, the microchannel-plate input and output, and the anode are held at four different voltages spanning 3–4 kV. For convenience, these four voltages may be floated with respect to ground. Fig. 3 shows typical operating voltages. Simple RC low-pass filters remove ripple and noise. The 9 V battery floated between the field wires and the microchannel-plate input prevents any secondary electrons emitted at the field wires or the electron-multiplier holder from reaching the microchannel plate. This ensures that if a single secondary electron from a background event hits a field wire and ejects more secondary electrons they would not reach the microchannel plate and fire several pores. We later found that this is not a problem since the mean secondary-electron yield for an electron on gold reaches a maximum of only 1.46 secondary electrons at 750 V.³⁵ Nonetheless, the 9 V potential increase may prevent some background electrons from reaching the microchannel plates.

III. PERFORMANCE

We first discuss the electron multiplier, which determines certain overall characteristics of the detector, and the multiplier's response to a single secondary electron from the dynode. Next we look at the detector response to ions of various species and energies and to background and dark noise. We compare the pulse-height distribution of

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Fig. 3 Schematic diagram showing typical operating voltages and equipment used during testing. The ammeter integrates the anode current with a 1 s time constant and a least count of 1 nA.

the ion signal to the distributions of the background and dark-noise, and discuss the effect of discrimination level on ion-counting efficiency and background-count rate in order to evaluate the overall performance of the detector in terms of dark-noise or background rate as a function of counting efficiency. Except as noted, the results presented are from tests in the mass spectrometer before the detector was installed in the cyclotron.

A. Pulse-height distribution in response to single electrons

In order to measure the pulse-height distribution of pulses from single-electrons incident on the microchannel plate, we illuminated the dynode with UV photons from a mercury-vapor lamp through a window in the mass spectrometer. This yielded a few hundred photoelectrons per second at the dynode, which fired the microchannel plate one electron at a time. The resulting single-electron distribution, Fig. 4, is the detector response to 1 keV electrons emitted at the dynode.⁶ At $V_m = 2.3$ kV and $V_d = 1.0$ kV, the mean charge of the single-electron distribution was 5.14 ± 0.10 pC, equivalent to an electron multiplication factor of 3.21×10^7 .

At $V_m = 2.3$ kV the FWHM is $(85 \pm 5)\%$ of the mean, or $(106 \pm 6)\%$ of the position of the peak. The distribution narrows as V_m increases, pushing the pulses further into saturation. Other references on Z-stack electron multipliers give values for the FWHM as small as 26% of the mean.³² A smaller FWHM indicates more effective saturation and may provide a steeper background-distribution tail, which would be better for our purposes. Below $V_m \approx 1.6$ kV the output pulses of this electron multiplier are not saturated and the multiplier operates in the current mode. The resulting pulse-height distribution has no peak but decreases monotonically.

B. Microchannel-plate gain and collection efficiency

The increases in microchannel-plate relative collection efficiency and gain as a function of incident-electron energy were measured by varying the voltage V_d across the drift gap. Single electrons were produced at the dynode by a UV source. We found that both collection efficiency and gain plateau at about 500 V,⁶ in agreement with manufacturer's data³⁰ for a similar type of electron multiplier. We operate with $V_d = 1$ kV.

Knowing the absolute gain of the electron-multiplier as a function of V_m is useful for several purposes. In pulse-counting mode ($V_m > 1.6$ kV) the gain is used to calibrate the ion pulse-height distribution in terms of secondary electrons emitted from the dynode. Similarly in current mode ($V_m < 1.6$ kV) the gain is used to calculate the ion current that

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Fig. 4 Pulse-height distribution at the output of the electron multiplier in response to single 1 keV electrons from the dynode. Background has been subtracted. The mean of the distribution is 5.14 ± 0.10 pC, so the electron-multiplier gain is $3.21 \times 10^7 \pm 1.9\%$.

produces the measured anode current. The gain is also used to calculate the maximum allowable ion count rate at different gains (Sec. IV.A).

The gain was measured directly, using single photoelectrons at $V_m = 2.3$ kV and $V_m = 2.5$ kV. At other values of V_m the gain was derived from data on the mean pulse height for 40 keV Cs or K ions. To use the ion data we assumed that the collection efficiency is independent of V_m . In fact the collection efficiency must decrease as V_m approaches zero. However, the gain varies steeply with V_m so the effect of any decrease in collection efficiency at low V_m is probably not a source of significant errors in the gain compared to sources such as uncertainties in detector voltages. Fig. 5 compares the curve of gain versus V_m for this detector with those for three other F4129 Z-stacks. Lo and Leskovar²⁵ tested one of them. The manufacturer³⁰ tested the other two stacks before and after processing with an “electron scrub” in preparation for installation in phototubes. The electron scrub makes the gain more uniform over the microchannel-plate surface and more stable over time and use.^{36,37} It also increases the V_m required to reach a given gain as shown by the “unscrubbed” and “scrubbed” curves for those two stacks. In this context the high gain that our unscrubbed stack reaches is consistent with Lo and Leskovar’s data. The larger error bars on our data below 1.6 kV result from systematic uncertainties such as instability of the ion source and hysteresis of the microchannel-plate gain following large changes in input current.

C. Ion-signal pulse-height distribution

We measured the pulse-height distribution of the detector output (in the pulse-counting mode) in response to ions of various incidence angles, species, and energies. This ion distribution should depend to first order on only these parameters (and on dynode properties), which determine the dynode’s secondary-electron yield distribution, not on the detector voltages, which determine the much narrower output distribution from a single electron. Nonetheless, the single-electron distribution is too wide to allow resolution of the individual peaks (at integer numbers of secondary electrons) that make up the ion distribution.

We tested the detector with positive-ion beams of ^{12}C , ^{23}Na , ^{39}K , ^{41}K , ^{85}Rb , ^{87}Rb , and ^{133}Cs at energies between 5 and 40 keV. Fig. 6 shows ion distributions representative of the range of measured distributions. These data were taken at different times and rates, so they include different amounts of background. They are consistent with nearly 100% ion-counting efficiency for a discrimination threshold near zero.⁶ The tails on the large pulse-height side of the distributions are longer for lighter ions and more

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Fig. 5 Gain versus microchannel-plate voltage for this and other F4129 electron multipliers. Data for tubes A and B show the effect of electron scrubbing. The manufacturer's data for tubes A and B, and the highest data point of the Lo and Leskovar data, are unpublished.

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Fig. 6 Pulse-height distributions for (a) 40 keV positive ions at $\theta = 80.0^\circ$, (b) 40 keV positive ions at $\theta = 82.3^\circ$, and (c) 5, 10, 20, and 40 keV $^{133}\text{Cs}^+$ ions at 73.7° , 77.8° , 80.5° , and 82.3° respectively. The smaller pulse heights at lower energies are partly due to the smaller incidence angles. Fig. 8 shows the corrected mean yield as a function of energy at $\theta = 82.3^\circ$. All curves are tracings from pulse-height analyzer photographs.

grazing incidence angles.⁶ The wide valley between the background at small pulse heights and the ion signal at larger pulse heights allows discrimination between them.

We measured the mean secondary-electron yield γ as a function of ion incidence angle θ , species, and velocity. For 40 keV Cs⁺ at $\theta = 80.0^\circ$, $\gamma = 19.5^{+2.0}_{-1.0}$ electrons and at $\theta = 82.3^\circ$, $\gamma = 23.9 \pm 0.4$ electrons. This increase is consistent with the trend of Dietz's data¹⁹ showing the approximate secant dependence of γ with θ for $\theta \leq 80^\circ$.⁶ Fig. 7 shows the secondary-electron yield dependence on ion species for this and previous data.^{16,19,38} The results are qualitatively similar after correcting for incidence angle. However, despite the fact that we took these data with higher ion energy and incidence angle, both of which should increase the secondary-electron yield, the yield is not much higher than the yield Dietz measured at $\theta = 80^\circ$. This indicates that additional effort to optimize dynode preparation might increase the secondary-electron yield. This would allow the use of higher discrimination thresholds resulting in lower background rates at the same collection efficiency.

Previous authors have shown that, for a given ion species, the secondary-electron yield is approximately proportional to ion velocity minus a threshold velocity of about 5×10^6 cm/s.^{16,39} Fig. 8 shows data for this detector before and after corrections to remove the effect of changes in incidence angle with ion velocity. The corrections are necessary because we did not adjust the orientation of the detector with respect to the beam to cancel the increased curvature of the lower-energy beam. We did adjust the slit position to center the beam on the dynode. We calculated the actual incidence angle for each velocity and made corrections, by interpolation of our data at 82.3° and 80.0° and Dietz's data¹⁹ below 80° for a plasma-anodized dynode, to arrive at the corrected yield at 82.3° as a function of velocity. We find a threshold velocity of $(3.6 \pm 0.7) \times 10^6$ cm/s for secondary electron emission. This is slightly lower than the 5×10^6 cm/s quoted above.

In summary, the detector's ion distribution appears to be proportional to the secondary-electron yield distribution as we expected. The detector response as a function of various ion parameters is consistent with other results in the literature.

D. Dark-noise distribution

The dark noise is the lower limit of the detector background. Because microchannel-plate electron multipliers are usually used to count pulses from single electrons, previous investigators have not explored the dark-noise distribution at the larger pulse heights that are relevant to ion detection. Fig. 9 compares the integrated pulse-height

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Fig. 7 Mean secondary-electron yield for positive alkali metal ions and $^{12}\text{C}^+$. For the data shown from this work ($\blacktriangledown$), the ions approached the detector with an energy of 40 keV and gained an additional 1 keV falling through the drift-gap field onto the dynode.

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Fig. 8 Mean secondary-electron yield versus ion velocity for Cs^+ ions. The calculated incidence angle is shown on the right-hand axis. The measured yield (●) at each energy and each angle θ was corrected to the expected yield (■) at the same energy for $\theta = 82.3^\circ$. The corrected yield shows the effect of velocity on yield at a fixed ion incidence angle. It is coincidental that the corrected points fall exactly on a straight line, since the error bars are large. The actual energies and velocities at impact are shown. In each case 1 keV of the impact energy was gained falling through the drift-gap field onto the dynode.

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Fig. 9 Integrated pulse-height distributions of dark noise at various values of V_m . Spline curves are fit through data points approximately one secondary electron apart. Representative statistical error bars are shown. The statistical uncertainties are given by Poisson statistics using the number of counts. The number of counts above a given threshold may be calculated from the rate plotted in this figure and the measurement times of 1.8×10^4 s for the 2.3 kV data and 3.0×10^3 s for the data taken at other voltages.

distributions for dark noise at various V_m before the electron multiplier was exposed to air. Although the statistics are not conclusive, the data indicate that the dark-noise rate falls as V_m increases from 1.9 to 2.3 kV. The rate rises again as V_m increases to 2.7 kV. Regardless of discrimination-threshold setting, $V_m = 2.3$ kV is optimal to minimize dark noise. The reason that an optimum exists may be that there is more field emission at higher V_m and less saturation of the single-electron distribution at lower V_m (as indicated by the shape of the 1.9 kV curve). Each microchannel-plate electron multiplier is different and requires individual optimization. In general, different V_m might be optimal at different discrimination thresholds. Fig. 10 shows that after exposure to air $V_m = 2.3$ kV is still optimal.

It is possible that if the electron multiplier were operated for additional time at $V_m > 2.3$ kV, the dark-noise rate at $V_m > 2.3$ kV might decrease. As V_m was increased to a higher value for the first time, the dark-noise rate distribution increased initially, then decreased asymptotically to an apparently stationary distribution. We did not study the time dependence of this decrease. We have operated the electron multiplier a total of about 500 hours, mostly at $V_m = 2.3$ kV. V_m was above 2.3 kV for less than one tenth of the time. Except as noted, data and results presented in this paper are for $V_m = 2.3$ kV.

Fig. 10 includes the integrated pulse-height distribution for 40 keV ^{133}Cs ions for use in comparing background to signal. The signal-to-noise ratio is not improved by raising the discrimination threshold above the point where the signal drops more steeply than the dark noise. Fig. 10 shows that there is no advantage in excluding counts above an upper discrimination threshold. Above any reasonable lower threshold the dark noise initially drops more steeply than the signal. The fraction of signal counts remaining above an upper threshold will always be larger than the remaining fraction of dark-noise counts. It would therefore be counter-productive to exclude counts above an upper discrimination threshold since this would cut out a larger fraction of the signal than of the background.

The total dark-noise rate for pulse heights above 0.5 secondary electrons ranges from 1 to 3 s^{-1} as V_m is varied from 1.9 to 2.7 kV. These rates are found both before and after exposure to air. Electronic noise from sources such as the amplifier does not contribute because, unlike other dark noise, it is not multiplied by the high-gain electron multiplier. For the F4129 phototube that was tested by Lo and Leskovar,²⁵ the total dark-noise rate from the stack (with the photocathode backbiased) was 5 s^{-1} with $V_m = 2.4$ kV and a pulse-height threshold of 0.13 secondary electrons. We believe the cause of dark noise at small pulse heights is thermal emission and field emission of

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Fig. 10 Integrated pulse-height distributions, after exposure of the electron multiplier to air, of dark noise at various values of V_m , and for the 40 keV $^{133}\text{Cs}^+$ signal at 2.3 kV. Spline curves are fit through data points approximately one secondary electron apart. Representative statistical error bars are shown. The statistical uncertainties are found as described in the caption for Fig. 9. The measurement times are 5.6×10^4 , 2.8×10^5 , and 7.7×10^4 s, for the 2.1, 2.3, and 2.5 kV data respectively.

electrons. The mean height of such pulses is expected to be ≤ 1 secondary electron depending on whether the electron is emitted at the dynode or at a point along a microchannel-plate pore. Fig. 9 and Fig. 10 show that most dark noise is in fact near or below the height of a pulse from a single secondary electron.

Although most dark-noise pulses are small, Fig. 10 shows that the dark-noise distribution has a tail which extends beyond 40 secondary electrons at $< 10^{-5} \text{ s}^{-1}$. We believe the causes of these infrequent, large dark-noise pulses in this detector are similar to the causes of such pulses in standard photomultiplier tubes.^{40,41} In both cases the large pulses are of two types: those that are intrinsically large and those due to fluctuations in multiplier gain which cause a typical background event to be amplified by the multiplier to an unusually large size. Possible sources of intrinsically large pulses, which fire many pores, include cosmic rays, intrinsic radioactivity (^{40}K in glass), high-voltage discharge, ion or photon feedback,⁴² and bursts of molecular ions and photons from ion pumps that arrive at the detector within the time constant of the discrimination electronics.

In general, statistical fluctuations in electron-multiplier gain are due to random microscopic multiplication processes. The distribution of fluctuations is broadened by nonuniformity of the multiplication surfaces and, in the case of microchannel plates, differences in the number of pores fired and differences in effective number of dynodes from pore to pore. The distribution is also affected by the extent to which the electron-multiplier gain is saturated and by the number of broken or malformed pores and the details of the random stacking of the three microchannel plates. Geometrically, on the basis of random stacking, no more than thirteen pores can be fired in the output plate for a single pore fired in the input plate,²⁶ but if plates are warped or damaged, this number can be larger.

Dietz has written extensively on the application of Polya, or compound Poisson statistics to ion detectors.^{10,16,17,41,43-46} According to Dietz, the Poisson distributions for the probable gain at each point on a multiplication surface combine into a Polya distribution for the overall gain. The Polya distribution is broader than the Poisson distribution, so on a statistical basis alone the dark-noise distribution should drop off less steeply than the tail of a Poisson distribution.

E. Threshold discrimination of background

In order to study the detector's ability to reduce background rates by discrimination, we introduced two sources of background, one at a time, into the mass spectrometer to

simulate the background we might encounter in the cyclotron. The sources we used were photons from a UV lamp and ions from an ion pump near the detector, which we turned on only for this purpose. (The ion pump may also emit some soft x rays.) We refer to these respectively as UV background and ion-pump background. The UV photons are from the 2537 Å mercury line (5e V). The ion-pump background has a maximum energy of 5 keV, the highest voltage in the pump.

In order to find the fraction of background pulses that remain above a given discrimination threshold, we subtracted the dark-noise distribution from the measured background distributions,⁶ and normalized to unity at 0.5 secondary electrons. The fractional reduction of UV and ion-pump backgrounds as a function of discrimination threshold is plotted in Fig. 11. The results are impressive. Pulse-height discrimination reduces backgrounds from UV and low-energy ions by a factor of 10^5 at thresholds of 9 and 15 secondary electrons, respectively. Each background decreases almost exponentially with increasing threshold. This may continue beyond the pulse height where our data lose statistical significance. The ion-pump background falls off less steeply, probably because some background ions emit more than one secondary electron at the dynode.

F. Ion-counting efficiency versus dark-noise and background rates

We compare ion distributions to dark-noise and background distributions, and eliminate discrimination threshold as the independent variable to find dark-noise and background rates as direct functions of ion-counting efficiency. This indicates the overall performance of the detector. We present results from data taken with $V_m = 2.3$ kV after the electron multiplier was exposed to air. Fig. 12 plots background reduction data (from Fig. 11) against counting efficiency, for 40 keV $^{12}\text{C}^+$ and $^{133}\text{Cs}^+$, at $\theta = 82.3^\circ$ (from Fig. 4b). The detector can provide large reductions of background even at 99% counting efficiency. Fig. 13 graphs dark-noise rate against ion-counting efficiency for various ions at $\theta = 82.3^\circ$. Fig. 13 is derived from the ion and dark-noise data shown in Fig. 4b,c and Fig. 10. The counting efficiency, expressed as the fraction of signal pulses above threshold, is plotted on Fig. 13 for use in comparing the signal to noise for different choices of counting efficiency.

Fig. 13 clearly illustrates the tradeoff between dark-noise and counting efficiency. By sacrificing some counting efficiency the detector can achieve very low dark-noise rates. The figure shows the improvement in both lower dark-noise and higher counting efficiency with increased ion energy. Doubling the ion energy decreases the dark-noise rate by a

XBL 8610-11750

Fig. 11 Background reduction versus pulse-height threshold. The curves are integrated pulse-height distributions for UV and ion-pump backgrounds. Dark noise has been subtracted and the curves have been normalized to unity at 0.5 secondary electrons. The central curves are the mean values and the upper and lower curves are $\pm \sigma$.

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Fig. 12 Background reduction versus counting efficiency. The fractional reduction of background is plotted for (a) 40 keV $^{133}\text{Cs}^+$ and (b) 40 keV $^{12}\text{C}^+$, both at $\theta = 82.3^\circ$.

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Fig. 13 Dark-noise rate versus counting efficiency. This figure indicates the overall performance of the detector. For the 40 keV data the incidence angle is 82.3° . For the 5, 10, and 20 keV data the incidence angles are lower as explained in Sec. III.C. The increase in the dark-noise rate for lower energies is due in part to the smaller angles. The curve labeled "signal" is the counting efficiency (expressed as the fraction of signal pulses above threshold) plotted against itself, for comparison to the dark noise.

factor of 8–9 at the same counting efficiency. (The counting-efficiency data from Fig. 4c was not corrected to eliminate the effect of different incidence angle θ . Thus a portion of the factor of 8–9 decrease in dark noise is due to increasing θ , rather than doubling the energy.) Fig. 13 shows that when counting C^+ the dark-noise rate is higher for counting efficiencies above 97% than it is for Cs^+ at the same energy. This is because the pulse-height distribution is wider for C^+ than for Cs^+ (Fig. 4b), so a larger fraction is at low pulse height. Similarly, the dark-noise rate is lower for C^+ at counting efficiencies below 97% because the mean pulse-height of the distribution is higher for C^+ than for Cs^+ .

Data taken in the mass spectrometer (Fig. 13) indicate that the detector can count 36 keV C^+ at 50% efficiency with a dark-noise rate of $5 \times 10^{-5} s^{-1}$. The best we could hope to do in the cyclotron would be to suppress the background to the level of dark noise alone. In fact, in order to increase the effective dynode area (Sec. IV.C) in the cyclotron we chose to use a less-grazing ion-incidence angle, about 75° , compared to 82.3° for the data used in Fig. 13. This is less advantageous insofar as the median yield at the smaller angle should be about 40% lower, or about 18 secondary electrons per carbon ion. The correction for detecting $^{14}C^-$ instead of $^{12}C^+$ is small by comparison. In the cyclotron we operate at $V_m \approx 2.0$ kV. The expected dark-noise rate is a little above the value for $V_m = 2.1$ kV in Fig. 10, $7 \times 10^{-4} s^{-1} \pm 16\%$. If the background in the cyclotron is similar to the ion-pump background, Fig. 11 indicates that a discrimination threshold of 18 secondary electrons should reduce its (unknown) rate by a factor of $\sim 10^6$. In fact we obtained a background rate in the cyclotron, at 50% counting efficiency, of $6 \times 10^{-4} s^{-1} \pm 10\%$, in agreement with the expected dark-noise rate to within the uncertainties. Thus the detector is successful in reducing the cyclotron background rate to nearly the rate of the dark-noise alone.

G. Stability of gain, signal, and background, after exposure to air

An increase in the dark-noise rate may have taken place after the detector was exposed to air during tests in the mass spectrometer. This increase can be interpreted as an increase of roughly 25% in the pulse height of the dark-noise distribution relative to the pulse height of the single-electron peak. However, the apparent increase may be due to errors in early, inconsistent measurements of the electron-multiplier gain. The tests in the cyclotron spanned 6–12 exposures to air. In later tests the pulse height of the background distribution appeared to be larger relative to the pulse height of the ion signal. This may be due to ion-beam changes, an electronic-noise increase, or dynode contamination. If the apparent increases of background pulse height in the mass spectrometer and cyclotron were

real and continue with longer use they may imply limitations on useful life of the detector.⁶ The electron scrubbing (Sec. III.B) that occurs during use of a microchannel-plate stack can reduce the overall gain^{33,37} for both ion signals and the background. However, we know of no attribute of Al_2O_3 dynodes or microchannel-plate electron multipliers that should cause an increase in the pulse height of background relative to that of ion signal in this detector design.

H. Electron multiplier damage from high-voltage discharge

During early tests in the mass spectrometer, a sudden current load caused the high-voltage supplies at both ends of the microchannel-plate to trip off as we tried to increase the voltage V_d between the dynode and the microchannel face from 2 kV to 3 kV.⁶ We believe that a piece of dust, found later on the dynode, caused a high-voltage discharge between the dynode and the microchannel face, which tripped the supplies. After this discharge, spontaneous pulses appeared in the dark-noise pulse-height distribution with a peak at about 0.25 secondary electrons. Initially the rate of these pulses was 300 s^{-1} but by the next day the rate had fallen to about 10 s^{-1} . The pulses stopped within a few days but reappeared occasionally at rates between 10 and 130 s^{-1} for a duration of a few minutes to a few hours. The pulses reappeared 20–30 times over a 5 month period of almost daily use. These spontaneous pulses are probably caused by field emission. Other investigators refer to similar pulses as hot spots.^{37,47}

In our case the spontaneous pulses may be the result of local damage in the microchannel plates caused by high current density during the initial discharge that tripped the supplies. The pulses usually appear only after we increase the microchannel-plate voltage V_m , which could cause field emission to start in the microchannel-plate pores but not at dust on the dynode. The damage occurred before the electron multiplier was exposed to air, and before we made measurements for any of the results presented in this work.

There is some indication that the damage, or some other effect of use, increased the amplitude of the tail to the left of the peak in the single-electron pulse-height distribution. The tail to the right of the peak was not affected. The spontaneous pulses do not seem to affect the detector's counting efficiency or background rates because typical discrimination thresholds are far above the height of these pulses. We did not find and remove the dust until we finished the controlled mass-spectrometer tests. This experience underscores the need for cleanliness while assembling the detector.

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If V_m is turned up too quickly when the electron multiplier is first used, there is danger that bursts of pulses from desorbed gases can run away and damage the microchannel plates in less than 1 msec.⁴⁸ At the same V_m the gain can vary by orders of magnitude between electron multipliers of the same model. Therefore the timing rather than the amplitude of the pulses is the best indicator of whether the pulse activity has decreased sufficiently to permit further increase of V_m . A multichannel scaler with a discrimination threshold just above the level of the electronic noise was used to measure the rate of dark-noise pulses. We increased V_m in 100 V increments to 1500 V and in 50 V increments to 2750 V. At each new voltage the rate and intensity of bursts of pulses increased. After a few minutes to a few hours, the bursts disappeared. We increased the voltage slowly enough to ensure that the largest pulse rate during bursts was no more than 10 times the average pulse rate.

IV. OPERATING RANGES

A. Dynamic range and upper limit on anode current

The top of the detector's dynamic range is determined by the maximum ion-count rate. The bottom of the range is determined by the dark-noise rate. Fig. 13 shows that a dark-noise rate of 10^{-4} s^{-1} is possible for 40 keV ions at 50–70% counting efficiency. The maximum ion-count rate results from a limit on the electron-multiplier anode current, which flows from the microchannel-plate output pores to the anode. The manufacturer³⁰ recommends that the integrated anode current I due to electron multiplication should not exceed 10% of the strip current I_s that flows through the microchannel-plate stack in its quiescent state with no counts. This limits $I \leq I_{\max} \equiv 0.1 I_s = 0.1 V_m / R_m$, where V_m and R_m are respectively the voltage and resistance across the microchannel-plate stack in the quiescent state.⁶ The value of R_m varies between microchannel-plate electron-multiplier types and between individuals of the same type. Choosing a low R_m would permit a higher $I_{\max}$.

Anode currents in excess of the nominal limit $I_{\max}$ cause substantial gain variations²⁷ and, according to the manufacturer,³⁰ possible damage to the microchannel-plate stack. The manufacturer has run microchannel plates at currents $I \geq 100 I_{\max}$ without damage or obvious hysteresis.³⁰ However, others have observed hysteresis following high anode currents.⁴⁹ This electron multiplier showed hysteresis (a temporary gain decrease of 59%) following gain tests (Sec. III.B) involving high ion currents at low V_m and gains as low as unity. In these tests the anode current reached at least $I = 2 I_{\max}$ and perhaps much higher. The gain recovered to the previous level by the following day when it was next tested. Another effect of high currents in this detector is the damage discussed in

Sec. III.H, which was presumably caused by an excessive local current density. In the cyclotron the detector has been run at ion currents high enough to cause anode currents an order of magnitude or more above the nominal limit. Following use at high ion currents the gain returns to its previous level after a few minutes to several hours.

We measured the decrease in the electron multiplier gain, as a function of $I/I_{\max}$, compared to the gain at $I = 0$. At $I = 0.5 I_{\max}$ the gain is $(4 \pm 1)\%$ lower and at $I = I_{\max}$ the gain is $(16 \pm 2)\%$ lower. Part of this gain decrease may be due to the fact that the microchannel-plate stack input and output are connected to the high-voltage supplies through voltage-dividing low-pass filters. The actual voltage V_m across the stack may sag as the current I increases. At $V_m = 2.3$ kV, a decrease in V_m of 27 V, or 1.2%, could account for a 16% gain decrease (Fig. 5).

Tests by the manufacturer³⁰ indicate that the gain decrease as a function of $I/I_{\max}$ depends on the local current density, and therefore on the fraction of the microchannel-plate area that carries the current. Their tests also indicate that the gain is a function of the time-averaged current for current-modulation frequencies above 100 Hz, but of the instantaneous current for frequencies below 10 Hz.

The detector's maximum ion-count rate is $C_{\max} = I_{\max} / (G_m \gamma e)$, where G_m is the electron-multiplier gain, γ is the mean number of secondary electrons emitted from the dynode (per ion) that are collected by the microchannel plate, and e is the electron charge. The dynode yield γ varies with ion energy and incidence angle and varies slightly with ion species (Sec. III.C). The microchannel-plate gain G_m increases approximately exponentially with V_m (Fig. 5). By reducing V_m to decrease the gain, $C_{\max}$ can be increased.⁶

Table 1. Values of $I_{\max}$, G_m , $C_{\max}$, and the dynamic range, at three choices for V_m . The values were calculated using $\gamma = 23.9$ secondary electrons per ion, the yield for 40 keV Cs at 82.3° incidence angle. The bottom of the dynamic range is defined by the dark-noise rate of 10^{-4} s^{-1} .

V_m	$I_{\max}$	G_m	$C_{\max}$ (ion/s)	Dynamic range	This choice of V_m achieves:
2.3 kV	82 nA	$10^{7.5}$	6.7×10^2	$10^{6.8}$	Lowest dark-noise rate.
1.6 kV	57 nA	$10^{3.7}$	2.9×10^6	$10^{10.5}$	Max ion rate in pulse-count mode.
1.2 kV	43 nA	$10^{0.3}$	5.6×10^9	$10^{13.8}$	Max ion rate in current mode.

B. Recovery time, maximum background rate, and low-energy background deflection

After a group of pores in the microchannel-plate stack is fired, the recovery time to replace the stored charge in the surrounding glass is on the order of 50–100 ms.^{25,26} If the same group of pores is fired before the charge is replaced, the gain and the resulting pulse height will be reduced.^{50,51} This gain reduction is different from the gain reduction discussed in the previous section, which depends on V_m .

In the output plate of the stack typically 7 adjacent pores out of a total of 1.3×10^6 are fired (Sec. II.F), though additional nearby pores may also supply charge. The gain will begin to decrease when the rate of secondary electrons collected is high enough that a significant fraction of the pores are fired within the recovery time. This rate is given by the total number of pores, 1.3×10^6 , divided by the 7 pores fired by one secondary electron, divided by the ~100 ms recovery time:

$$(1.3 \times 10^6 \text{ pores}) \times (7 \text{ pores/e}^-)^{-1} \times (100 \text{ ms})^{-1} = 1.9 \times 10^6 \text{ e}^-/\text{s}.$$

This assumes the secondary electrons are distributed uniformly over the 1.3×10^6 pores of the input plate. Since the electron multiplier collects a few tens of secondary electrons for each ion, the gain will decrease as the ion rate approaches 10^5 s^{-1} . This may require adjustment of discrimination thresholds for high count rates when the electron multiplier is in pulse-counting mode at low gain (Table 1).

It is important that the rate of background events, which usually fire a single pore, remain well below 2×10^6 input-pores fired per second. Otherwise the background rate could cause the gain to be reduced for ion-signal pulses. In an environment like that of the

cyclotron, with large numbers of low-energy background electrons or ions, the detector's ability to deflect low-energy background particles (Sec. II.C) is useful for reducing the rate of pore firings due to background. When the background energies are low enough, the electric field in the drift gap prevents even uncollimated background ions and electrons from reaching the dynode or microchannel plate and firing pores. The effectiveness of the deflection of background could be improved by increasing the distance that background particles must travel through the drift gap before reaching the dynode or microchannel plate.

C. Ion-beam size and incidence angle

The detector geometry causes there to be a tradeoff between the secondary-electron yield γ and the beam width w that intersects the dynode, because both depend on the ion-incidence angle θ . For a given dynode size, the product γw is constant to first order because $w(\theta) \propto \cos \theta$ and $\gamma(\theta) \propto \sec \theta$, where θ is measured from normal. At $\theta = 82.3^\circ$ the 13 mm wide dynode requires the beam to be focused to 1.8 mm in that direction. It is preferable to keep the ion beam away from the edges of the dynode. Otherwise secondary electrons may not reach the microchannel plate. Also, if the ion beam does not approach the edge of the dynode the detector output is less sensitive to beam position. However, a large secondary-electron yield is desirable. To increase both w and θ the dynode size could be enlarged. The secondary electrons from a larger dynode could then be focused onto the microchannel plate⁴ or a microchannel plate with the same area as the dynode could be used. Microchannel plates with dimensions above 10 cm are now available.

D. Operating pressures

Siegmund *et al.*⁴⁷ have operated Z-stack electron multipliers at pressures from 7×10^{-7} Torr to 1.5×10^{-5} Torr and found no change in the background rate over that range. The manufacturer guesses that there may be problems with microchannel-plate gain stability or aging at or above 10^{-6} – 10^{-5} Torr.³⁰ Aging refers to changes in electron-multiplier behavior, especially gain, which depend on the total integrated charge extracted during the electron multiplier's lifetime.³⁷ We have tested the detector in the cyclotron at pressures up to about 2×10^{-7} Torr with no apparent change in behavior. Most of the data presented in this work were taken at the mass-spectrometer base pressure of $1\text{--}3 \times 10^{-9}$ Torr.

E. Sensitivity to magnetic fields

The microchannel-plate stack is insensitive to magnetic fields up to 1 kG

perpendicular to the pores, or 2 kG parallel to the pores.⁴² This is due to the small pore diameter and the strong electric field within the pores. However, the detector as a whole is sensitive to magnetic fields strong enough to deflect secondary electrons in the drift gap.

A magnetic field B in the drift gap that is perpendicular to the electric field E will displace the collection point for each secondary electron in a direction parallel to the microchannel-plate face. If the magnetic field is too strong the electrons will return to the dynode without reaching the microchannel plate. The displacement D depends on B and on the distance s and the voltage V_d across the drift gap, as $D \propto B s^2 (V_d)^{-1/2}$, to first order. For $B = 10$ G, $D \approx 1$ mm.⁶ A much larger displacement would substantially reduce the effective area of the dynode.

A parallel B field causes the secondary-electron paths to be helical around an axis normal to the dynode. As the secondary electrons ejected by an ion travel toward the microchannel plate the B field prevents them from separating from one another as much as they would for $B = 0$. If the B field is too strong the electrons will not separate sufficiently to be independently multiplied in the microchannel-plate stack (Sec. II.E). This would result in lower pulse heights for ion signals. We do not know what separation between incident electrons is required for independent multiplication, but the separation in the present design appears to be sufficient. By imposing the condition that most electrons complete less than one-half orbit in the 1.4 ns time of flight from the dynode to the microchannel plate, we calculate an upper limit on B of 110 G.⁶ This will maintain nearly the same separation as for $B = 0$.

In the mass spectrometer, the magnetic field at the detector was 3–4 G in an unknown direction. In the cyclotron, a 6 mm thick iron shield reduces the B field to about 5 G at the position of the detector, which is immediately outside the poles of the cyclotron magnet. The B field is approximately parallel to the electric field in the drift gap. The detector has shown no adverse effects resulting from the B field in either application. In applications where magnetic shielding can not be used to reduce the magnetic field to acceptable levels, other possible solutions are to increase V_d or to decrease the distance from the dynode to the microchannel plate. For a transverse magnetic field the dynode can be offset with respect to the microchannel plate to correct for the magnetic deflection. The detector's dovetailed dynode slot makes this a straightforward adaptation.

F. Uniformity of response over microchannel-plate and dynode surfaces

In the cyclotron we are trying to achieve high sensitivity but we expect the accuracy of abundance-ratio measurements to be limited by statistics and systematics that are not attributable to the detector. However, in other applications to mass spectrometry, high accuracy requires the detector to be insensitive to small changes in incident ion-beam position. Then small errors in the magnetic field will not cause errors in measured isotope ratios when the B field is swept to scan the mass spectrum or to switch between ion beams of different masses. In such applications it is important for both the dynode and the microchannel-plate stack to have uniform response over their surfaces. Otherwise the counting efficiency at a given discrimination threshold will vary depending on where the ions hit the dynode.

Dietz¹⁶ concluded that the Al_2O_3 dynodes he made and tested show no variation in secondary-electron emission over their area. Manufacturer tests of image intensifiers show that there are no Moiré patterns in the output of stacked microchannel plates stimulated by uniform input from photocathodes.³⁰ This indicates that neither the random alignment of pores between plates in the stack, nor differences in collection efficiency between the webbing and the pores, cause observable gain variations over the active area. The absence of other observed gain variations in tests by the manufacturer and others^{30,32,33} indicates the absence of other possible causes of such variation, such as uneven gaps between plates, which would allow pores in some portions of one plate to fire larger numbers of pores in the next plate. Sec. II.F quotes limits on collection-efficiency variations over the active area. In the detector, we expect gain variations on a scale smaller than 1 mm to average out because the secondary electrons from a single ion fire pores over distances larger than 1 mm (Sec. II.E). If necessary the gain uniformity over the microchannel-plate area could be improved by electron scrubbing (Sec. III.B).

In the tests in both the mass spectrometer and the cyclotron, the beam emittance and the grazing-incidence angle caused some of the ions to hit near or beyond the edge of the dynode. This prevented us from testing the sensitivity of the detector to beam position. A uniform response is expected for an ion beam that is smaller than the dynode.

CONCLUSION

We have demonstrated that this detector can discriminate the signal of a full-energy ion from the actual background in the operating 36 keV cyclotron. The detector has achieved the very low background rate of $6 \times 10^{-4} \text{ s}^{-1}$ with 50% counting efficiency for

36 keV ions. The detector has been used to test rejection of nearby-mass ion backgrounds in the cyclotron.⁴ The small mass difference of 1/1800 between ^{14}C and ^{13}CH requires that the transmission of these background ions be suppressed by 8–11 orders of magnitude when the tuning frequency is changed by 1/1800. Experiments show that with this detector the cyclotron suppresses the transmission of the molecular-ion backgrounds by a factor of 2×10^{11} within the required frequency change. This is sufficient to date milligram samples of 30,000 year old carbon with less than 10% statistical uncertainty in the $^{14}\text{C}/^{12}\text{C}$ ratio.

We expect that the insensitivity of the detector to ion-beam position will be advantageous in standard mass spectrometry, where accurate isotope-ratio measurements require insensitivity to beam-position errors. The detector's performance in reducing background should also be useful in general ion detection and mass spectrometry. The dark noise rate is 10^{-4} s^{-1} for thresholds that allow counting 40 keV ions with 50–70% efficiency, or 10^{-2} s^{-1} for counting 5 keV ions with about 50% efficiency. This makes it possible to detect ions of trace elements or isotopes at similar low count rates. This can facilitate standard mass spectrometry on very small samples. The detector can reduce low-energy background by factors of 10^2 – 10^4 at discrimination thresholds that allow a counting efficiency of 99% for 40 keV ions or about 50% for 5 keV ions. This should allow low-rate *in situ* detection of trace ions in equipment with large backgrounds of low-energy ions, electrons, or photons.

Data obtained with the detector in the cyclotron indicate that with a beam current four orders of magnitude higher the background will still be rejected sufficiently to measure ^{14}C reliably in old samples. We are installing a higher-current external ion source on the cyclotron.⁶ This will permit us to date real samples.

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