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Pulse-height distribution of output signals in positive ion detection by a microchannel plate

Kenji Furuya[*], Yoshihiko Hatano

Department of Molecular and Material Sciences, Kyushu University, 6-1 Kasuga koen, Kasuga, Fukuoka 816-8580, Japan

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Abstract

Positive ions produced by a 120 eV electron impact on H_2, He, CH_4, N_2, CO_2, and Kr were detected with a microchannel plate (MCP), and the pulse-height distributions (PHDs) of the output signals were observed. As a result, the half width at half maximum (HWHM) of the region above the peak of the PHD was almost independent of the kind of ion. This finding demonstrates that the HWHM is due only to the amplification of the secondary electrons that emerged as a result of the collision of the ions with the surface of the MCP. The dependence of the peak position and the HWHM against the potential difference applied between the front and back of the MCP was also examined. It was found that the plots of the HWHM as a function of the potential difference applied to the MCP could be fitted by a linear line very well. A formula that can reproduce the observed PHDs is presented as a function of the potential applied to the MCP and the mass number. A relation of the mean peak height in the PHD to the potential applied to the MCP and the mass number is also presented. (Int J Mass Spectrom 218 (2002) 237–243)
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Keywords: Positive ion; MCP; Pulse-height distribution; Detection efficiency

1. Introduction

Many researchers with considerable experience in detecting ions with a microchannel plate (MCP) or a channel electron multiplier (CEM) would realize that the detection efficiency of ions depends significantly on the properties of each ion, e.g., mass, charge, energy, and chemical structure. There is still not much information on ion dependence; however, many studies deal with the dependence of the detection efficiency of the MCP and CEM on the incident energy of electrons, ions and energetic photons [1]. One reason for this is that the detection efficiency depends strongly on the conditions under which an ion detector is used. Some researchers have determined the detection efficiency of each ion individually in their experimental systems, for example, when they wanted to determine experimentally the absolute values of ionization cross-sections for atoms and molecules [2–4].

The absolute values of the detection efficiency of ions, which depends on the kind of ions, are not always necessary for every study; the relative values are sufficient for some studies, such as a study of determining the branching ratio of fragment ions. Examining the pulse-height distribution (PHD) of output signals from an ion detector for several kinds of ions does not present any information about the absolute detection efficiency of the ions, but it does present the important information about the relative detection efficiency of different ions. Measuring the PHD, it

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[*] Corresponding author. E-mail: furuya@mm.kyushu-u.ac.jp

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is easy to estimate the ratio of output signals falling below a discriminator threshold to the total output signals from the detector in an ion counting system. When many ions are produced quasi-continuously with a continuous excitation source and several ions are produced simultaneously with an intense pulsed excitation source such as a pulsed laser, an observable signal in the measurements is the mean peak height in the PHD because the output signal from the detector is the superposition of the output pulses. In such a case, the mean peak height in the PHD is also useful for calibrating the intensity of the ion signals.

In this report, we present the PHDs of output signals from an MCP for ions produced by electron impact on H_2, He, CH_4, N_2, CO_2, and Kr. In addition, the dependence of the PHD on the potential difference applied to the MCP is examined. On the basis of these data, a formula that can reproduce the observed PHDs as a function of the potential applied to the MCP and the mass number is derived. Additionally, a relation among the mean peak height in the PHD, the potential applied to the MCP and the mass number is also derived. The purpose of this work is to provide practical data for calibrating the intensity distribution of mass spectra observed with a commonly used two-stage MCP.

2. Experimental

A fragment ion–photon coincidence apparatus by electron impact, which has already been described in detail elsewhere [5], was used in the present experiment. Briefly, its vacuum chamber consists of a molecular beam source, an electron beam source, and a collision chamber, which are differentially pumped. A supersonic molecular beam of a sample gas collided continuously with an electron beam of an incident energy of 120 eV. The operating pressure of the vacuum system was 9.0×10^{-6} Torr under the measurements. Actual pressure near the MCP would be slightly lower because a turbomolecular pump (160 L/s) evacuated the TOF tube independently. The collision chamber was evacuated with another turbomolecular pump (1500 L/s). The produced ions were extracted into a Wiley–McLaren-type time-of-flight (TOF) mass spectrometer by a static electric field of 10 V/cm applied to the collision region and then detected with an MCP.

Table 1
Branching ratios of the positive ions produced at 120 eV electron impact of sample gases

Sample	Branching ratio
H_2	H_2^+ (∼100%)
He	He^+ (∼100%)
CH_4	CH_4^+ (49%), CH_3^+ (40%), CH_2^+, CH^+, C^+, etc. (11%)
N_2	N_2^+ (96%), N^+, N_2^{2+} (4%)
CO_2	CO_2^+ (96%), O^+ (3%), CO^+, CO_2^{2+}, etc. (1%)
Kr	Kr^+ (82.8%), Kr^{2+} (16.6%), Kr^{3+}, Kr^{4+} (0.6%)

No pulsed electric field was applied to the TOF mass spectrometer because it caused pulsed noise signals to the MCP output and made it impossible to measure a PHD. Therefore, mass selection was not carried out, although the TOF mass spectrometer was used for the PHD measurements. In order to determine the branching ratio of ions produced from each sample, the TOF mass spectra were observed by applying a pulsed electric field in the collision region and pulsing the incident electron beam. The branching ratios of the produced ions are summarized in Table 1. Most of the detected ions were the parent ions, except for CH_4. The branching ratio of the H^+ ion produced from H_2 and CH_4 was negligible under the experimental condition of 10 V/cm applied to the collision region because the large velocity of the H^+ ion prevents its detection, as discussed in our previous reports [6].

The ion count rate was kept at 5000 s^{-1} in order to avoid the saturation of the MCP. The output pulse from the MCP was amplified with a preamplifier (EG&G Ortec, 9301; gain = 10) and a fast amplifier (EG&G Ortec, FTA820A; gain = 200). The shape of the output pulse was measured using a storage oscilloscope (Sony Tektronix, TDS620), and the digitized data of the pulse shape were sent to a personal computer (Epson, PC-286V) to obtain the pulse height. Repeating this operation 8000 times, we obtained a PHD. The

MCP used in this experiment was a two-stage, single anode MCP (Hamamatsu, F-1552-21S; channel diameter = 12 μm, effective diameter = 27 mm). The gain of an MCP output decreases exponentially with the increase of its accumulated output charge: for example, the relative gain becomes half after a new three-stage MCP operated for 600 h under a count rate of 5500 counts/s at $V_{MCP} = 2.4\,kV$ [7], where V_{MCP} is potential difference between the front and back of the MCP. The MCP used for the PHD measurements had been used in the ion counting system almost every day for the last 5 years. The decrease in the gain under the PHD measurements is the negligible.

High voltage from a power supply was divided using a few registers and then applied to the MCP. The voltage applied to the front side of the MCP (V_{in}), the absolute value of which is nearly equal to the kinetic energy of the ions, has a value of $|V_{in}| = 1.05V_{MCP}$. In the present system, the anode of the MCP is equal to the ground potential, and V_{in} has a negative polarity. A condenser was used for removing a DC component included in the MCP.

3. Results and discussion

Fig. 1 shows the PHDs of the MCP output due to ions produced by electron impact on six kinds of sample gases at $V_{MCP} = 2.19\,kV$ and at $V_{in} = -2.30\,kV$, in which the abscissa is the absolute value of the pulse height after amplification. The solid curves in Fig. 1 show approximate curves of the observed PHDs, which will be described later. All of the PHDs shown in Fig. 1 have a threshold at 0.6 V. This threshold is due to the trigger level on a storage oscilloscope. The trigger level cut off the noise pulses of the MCP, which have lower pulse heights than the trigger level. There are no signals due to the noise, as shown in Fig. 1.

The following conclusions are obtained from Fig. 1:

(1) The peak position of the PHDs decreased with increasing the mass number of ions.

(2) The HWHM of the region above the peak was almost independent of the kind of ions.

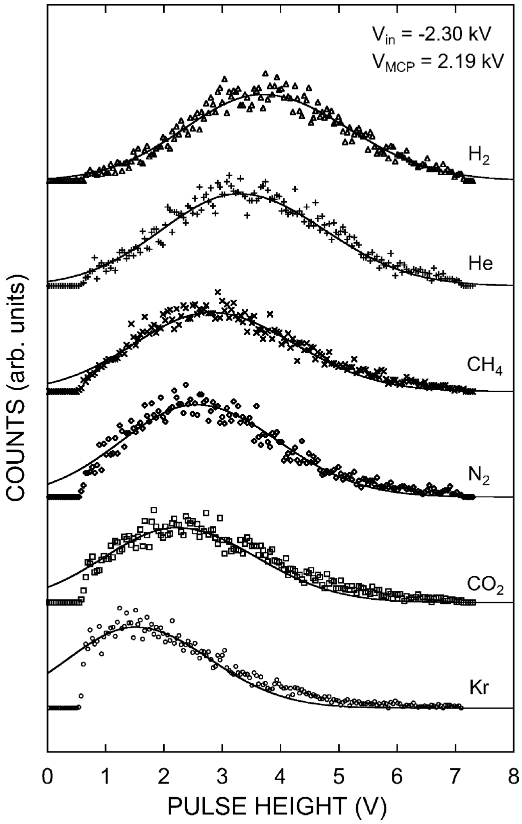

Fig. 1. PHDs of the MCP output due to ions produced by electron impact on six kinds of sample gases. $V_{MCP} = 2.19\,kV$ and $V_{in} = -2.30\,kV$. The solid curves have been obtained from Eq. (6). See the text.

The second conclusion indicates that the HWHM of the region above the peak is due to the amplification of the secondary electrons produced at the collision of the ions with the surface of the MCP.

Similar experiments were carried out under different conditions of V_{MCP}. Fig. 2 shows the PHDs of the MCP output due to ions produced by electron impact on four kinds of sample gases at $V_{MCP} = 1.95\,kV$ and at $V_{in} = -2.05\,kV$. The solid curves in Fig. 2 are the approximate curves of the observed PHDs, which will be described later. The PHDs obtained from CO_2 and Kr under these conditions did not have a peak in the PHD. The threshold at 0.3 V in Fig. 2 is due to the trigger level of the storage oscilloscope, cutting

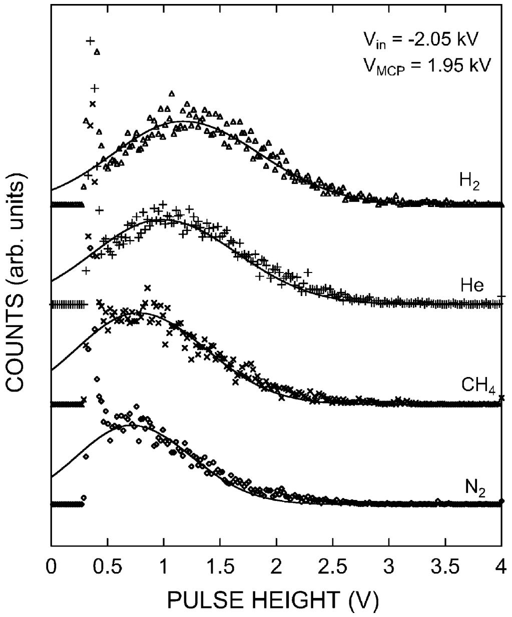

Fig. 2. PHDs of the MCP output due to ions produced by electron impact on four kinds of sample gases. $V_{MCP} = 1.95\,kV$ and $V_{in} = -2.05\,kV$. The solid curves have been obtained from Eq. (6). See the text.

partially off the noise pulses. The pulse height of the signals decreased in comparison with that in Fig. 1, and the noise of the MCP was clearly observed in the 0.3–0.5 V region of Fig. 2.

In order to estimate accurately the peak position and the HWHM of the region above the peak, all the PHDs observed were approximated with a polynomial of degree nine. The peak positions as a function of the averaged mass numbers, which were obtained on the basis of the branching ratios indicated in Table 1, are shown in Fig. 3. The PHD and the peak position of the PHD depend on the charge of the ion. The PHD peak position increases with the charge of the ion [8]. This fact indicates that the peak position of the PHD depends on the m/e value. The averaged m/e value was then used for the plot of Kr in Fig. 3.

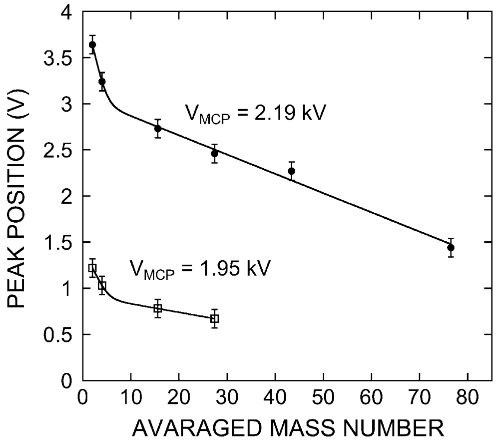

Fig. 3. Plots of the peak of the PHD as a function of the averaged mass numbers: (●) $V_{MCP} = 2.19\,kV$; (□) $V_{MCP} = 1.95\,kV$.

It was difficult to obtain a simple relation which would describe the correlation between the mass number and the peak position. Nevertheless, it would be valuable to provide a simple function that can reproduce the experimental data. The solid curves shown in Fig. 3 are expressed with the following function:

$$\text{Peak position} = a\exp(-bM^2) - cM + d, \qquad (1)$$

where M denotes the averaged mass number, $a = 0.823$, $b = 0.0732$, $c = 0.0206$, and $d = 3.07$ at $V_{MCP} = 2.19\,kV$, and $a = 0.408$, $b = 0.0660$, $c = 0.00932$, and $d = 0.925$ at $V_{MCP} = 1.95\,kV$. The exponential function on the right-hand side in Eq. (1) is responsible only for the reproduction of the peak positions in the PHDs of H_2 and He, and the second and third terms are for higher mass numbers.

The PHDs of H_2 and He, shown in Fig. 1, seem to have two peaks near the top. Such a splitting of the peak was not observed in the cases of the other samples or in the cases of H_2 and He at $V_{MCP} = 1.95\,kV$, as shown in Fig. 2. In addition, the simulation of the PHDs with a polynomial of degree nine showed a single peak. We then analyzed all the PHD data by assuming that they have a single peak.

Fig. 4 shows the plots of the HWHM of the region above the peak of the PHD as a function of V_{MCP}, in which the solid lines are expressed with the following function:

$$\text{HWHM} = aV_{MCP} + b, \qquad (2)$$

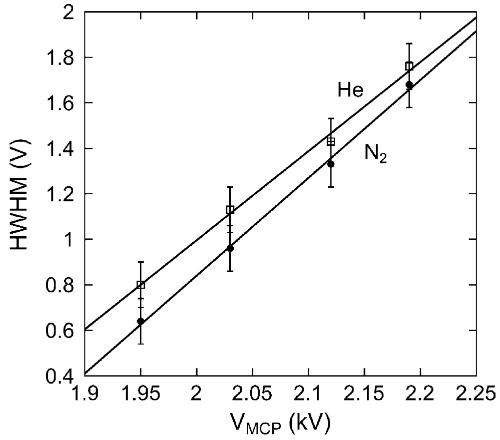

Fig. 4. Plots of the HWHM of the region above the peak of the PHD as a function of V_{MCP}, in which the solid lines are linear lines obtained by fitting the plots: (●) N_2; (☐) He.

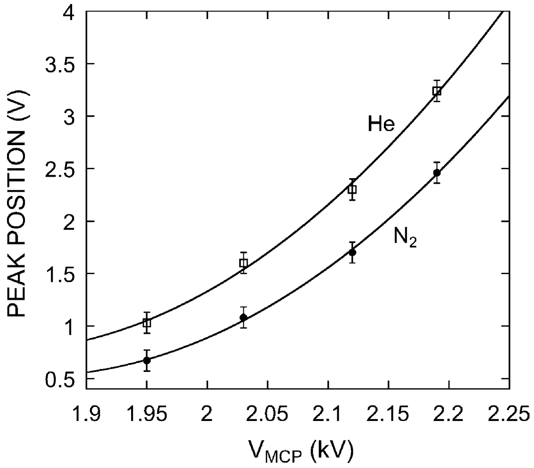

Fig. 5. Plots of the peak of the PHD as a function of V_{MCP}, in which the solid curves are quadratic curves obtained by fitting the plots: (●) N_2; (☐) He.

where $a = 3.91$ and $b = -6.83$ in the case of He, $a = 4.30$ and $b = -7.76$ in the case of N_2, and V_{MCP} is in the kV unit. The HWHM of the region above the peak of the PHD is due to the amplification of the secondary electrons, as has been described above. It is then expected that the HWHM depends on V_{MCP}. In the present experiments, the V_{MCP} was varied only by 10%. Such small variation of V_{MCP} lead to a simple linear relation between the HWHM and V_{MCP}. This finding also demonstrates that the HWHM is independent of the kinetic energy of ions colliding with the surface of the MCP, even if the kinetic energy of the ions changes as V_{MCP} is changed.

Fig. 5 shows the plots of the peak positions of the PHD as a function of V_{MCP} for He and N_2, in which the solid curves are expressed with the following quadratic function:

$$\text{Peak position} = aV_{MCP}^2 + bV_{MCP} + c, \tag{3}$$

where $a = 18.3$, $b = -66.6$, and $c = 61.4$ in the case of He, $a = 17.0$, $b = -62.9$, and $c = 58.8$ in the case of N_2, and V_{MCP} is in the kV unit. The detection efficiency of the ions depends strongly on the kinetic energy of the ions when the energy is around 2 kV [8]. The peak position, then, depends on both the kinetic energy of the ions and V_{MCP}. Therefore, the plots shown in Fig. 5 were successfully fitted by quadratic curves.

The following function can reproduce all the peak positions obtained in the present experiments as well as Eqs. (1) and (3) very well:

$$\begin{aligned}\text{Peak position} = {} & (-9.661V_{MCP}^2 + 41.70V_{MCP} - 44.17) \\ & \times \exp(-0.0336V_{MCP}M^2) \\ & + (6.82V_{MCP}^2 - 25.1V_{MCP} + 23.3) \\ & \times (-0.02M + 3),\end{aligned} \tag{4}$$

where V_{MCP} is in the kV unit. It should be noted that Eq. (4) holds under the condition $|V_{in}| = 1.05V_{MCP}$.

The following function could reproduce all the HWHMs observed as well as Eq. (2) very well:

$$\begin{aligned}\text{HWHM} = {} & (1.67 \times 10^{-2}M + 3.84)V_{MCP} \\ & - (3.97 \times 10^{-2}M + 6.67),\end{aligned} \tag{5}$$

where V_{MCP} is in the kV unit. The HWHM depends very slightly on the averaged mass number. The peak positions and the HWHMs observed are summarized in Table 2 with the values calculated from Eqs. (4) and (5). A common constant factor should be multiplied

Table 2
Peak positions and HWHMs in the region above the peak of the PHD

Sample[a]	$V_{\mathrm{MCP}} = 2.19\,\mathrm{kV}$		$V_{\mathrm{MCP}} = 1.95\,\mathrm{kV}$	
	Peak position[b]	HWHM[c]	Peak position[b]	HWHM[c]
H_2 (2)	3.64 (3.69)	1.70 (1.73)	1.22 (1.17)	0.78 (0.81)
He (4)	3.24 (3.29)	1.76 (1.73)	1.03 (0.98)	0.80 (0.79)
CH_4 (15.6)	2.73 (2.80)	1.75 (1.69)	0.78 (0.77)	0.70 (0.71)
N_2 (27.4)	2.46 (2.55)	1.68 (1.66)	0.67 (0.71)	0.64 (0.63)
CO_2 (43.4)	2.27 (2.22)	1.76 (1.61)		
Kr (76.5)	1.44 (1.53)	1.61 (1.50)		

[a] Values in the parenthesis are the averaged mass numbers obtained on the basis of the branching ratios indicated in Table 1.
[b] Values in the parenthesis have been obtained from Eq. (4).
[c] Values in the parenthesis have been obtained from Eq. (5).

by Eqs. (4) and (5) when the gain of an amplifier used in the experiment is changed.

The observed PHDs could be reproduced well with the following function:

$$f(V) = f_0 \exp[-\alpha(P - V)^2], \tag{6}$$

where

$$\alpha = \frac{1.1^2 \ln 2}{(\mathrm{HWHM})^2}, \quad \text{at } 0 \le V < P,$$
$$\alpha = \frac{\ln 2}{(\mathrm{HWHM})^2}, \quad \text{at } V \ge P, \tag{7}$$

and P denotes the peak position expressed in Eq. (4). HWHM in Eqs. (7) and (8) is expressed in Eq. (5), and f_0 is a constant. The curves obtained from Eq. (6) are shown in Figs. 1 and 2. Using a function expressed in Eq. (6), we can estimate the ratio of the output signals falling below a discriminator threshold to the total output signals from the detector in an ion counting system.

The mean pulse height is not equal to the peak position in the PHD because the observed PHD is not symmetrical with respect to the ordinate, including the peak position. We then calculated the mean pulse heights in the PHDs, using Eq. (6). The obtained mean pulse heights could be reproduced with the following function:

$$\begin{aligned}\text{Mean pulse height} &= (-3.063V_{\mathrm{MCP}}^2 + 14.59V_{\mathrm{MCP}} - 16.45)\\ &\quad \times \exp(-0.0468\sqrt{V_{\mathrm{MCP}}}M^2)\\ &\quad + (5.32V_{\mathrm{MCP}}^2 - 19.2V_{\mathrm{MCP}} + 17.52)\\ &\quad \times (-0.018M + 3.2).\end{aligned} \tag{8}$$

It should be noted that the dependence of the exponential function included in Eq. (8) on V_{MCP} is different from that in Eq. (4). The plots of the mean pulse heights against the averaged mass numbers are shown in Fig. 6, in which the solid curves obtained from Eq. (8) are also shown.

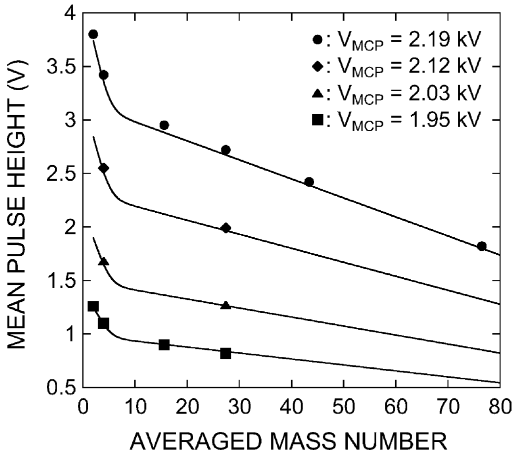

Fig. 6. Plots of the mean pulse heights as a function of the averaged mass numbers. The solid curves are obtained from Eq. (8).

In conclusion, we have observed the PHDs of the MCP output due to ions produced by electron impact on H_2, He, CH_4, N_2, CO_2, and Kr. We found that the peak position of the PHD is strongly dependent on the kind of ion; in contrast, the HWHM of the region above the peak is almost independent of the kind of ion. The present results strongly demonstrate, that in order to determine accurately the relative intensity of the ions detected with an MCP in a counting system, it is essential to estimate the magnitude of the ion signals falling below a discriminator threshold on the basis of the PHDs for the ions. The dependence of the mean peak height in the PHD on the mass number should be examined to calibrate the intensity in the ion signals in a detection system in which the output signal is observed as the superposition of the output pulses from the detector. Eqs. (6) and (8) would be useful for such a calibration, although these equations are derived on the basis of data obtained under limited experimental conditions. The constant factors included in all the functions we have derived should be adjusted for data obtained in different experimental system. It is, however, easy because we have described here the prescription for it.

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