Relative counting efficiencies of ion charge-states by microchannel plate

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Abstract

Relative detection efficiencies $D_{\phi}$ of ions with different charges and impact energies in single-ion counting mode with microchannel plates (MCP, Hamamatsu F1094-21S) have been examined for Li$q^+$, Ar$q^+$, Ba$q^+$ and Yb$q^+$ ions ($q = 1, 2$ and $p = 1, 2, 3$). The incident ion energy ranges from 1.1 to 15 keV. The efficiencies $D_{\phi}$ for a given atom, plotted as a function of incident ion energy $E_K$, lie on a unique curve. This comes originally from the fact that the secondary electron emission at the input channel-wall of MCP is dominated mainly by kinetic emission processes and little by potential emission processes in the keV energy range. When ions with different charges but the same $E_K$ value of a given atomic species are detected, almost equal detection efficiencies are ensured as far as $E_K$ is larger than 4 keV. Nearly equal detection efficiencies for singly and doubly charged ions accelerated by the same voltage are attainable at higher acceleration voltages for heavier ions, e.g., 5 kV for Ar$^+$ and Ar$^{2+}$ ions and about 10 kV for Ba$^+$ and Ba$^{2+}$ ions. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Ion detection in counting mode with a microchannel plate (MCP) or a channel electron multiplier (CEM) is widely used in electron collision and photoabsorption experiments involving ions. This technique is particularly important in ionization experiments of atoms or ions by photons, since the intensity of ions produced is generally too weak to be detected by the dc method. In experiments where the absolute number of ions produced is required, absolute detection efficiency of the detector (MCP or CEM plus electronics) would be
essential. In experiments where ions with different charges \( A^{q+} \) \((q = 1, 2, 3, \ldots)\) are involved and their relative intensities are required, the knowledge of relative detection efficiencies is essential.

Because of its importance, several experimental groups examined the detection characteristics of MCP or CEM for ions in their particular arrangement and counting system. Raven [1] studied relative detection efficiencies of inert-gas ions for a channeltron. He shows in his paper that the detection efficiencies, plotted as a function of kinetic energy of the ions incident on the channeltron, lie on a universal curve. Hellising et al. [2] also studied the detection of ions by MCP, and concluded that the efficiency is not affected by variation of mass and energy if an appropriate noise discrimination level is set and the ion energy exceeds approximately 5 keV. Recently, Luhmann et al. [3], in their photoelectron ion coincidence experiment, examined relative detection efficiencies of \( \text{Xe}^{q+} \) \((q = 1, 2, 3)\) ions by MCP, and obtained the incident energy dependence similar to that obtained by Raven [1]. A measurement of absolute counting efficiency by CEM for H, He, Ar and Xe ions was reported by Fricke et al. [4]. An experiment reported by Takagi et al. [5] is unique in which the gain characteristics of an MCP and a CEM for multiply charged (+4 to +13) ions of C, N, O, F, Ne and S were studied.

The purpose of this study was to examine the relative detection efficiency in single-ion counting mode of ions with different charges by a double assembly MCP of chevron type, for several atomic species. Hereafter we use the terminology “(relative) counting efficiency”. The demand for this study came from recent photoionization experiments on lanthanide atoms [6,7], Li atom [8–10], K atom [11], and \( \text{Xe}^+, \text{Xe}^{2+}, \text{Ba}^+, \text{Eu}^+ \) ions [12–17]. Although several related papers are available [1–5], it is not always apparent as to which data can be most appropriately referred to in each of these experimental photoionization studies. In general, the ion counting efficiency is considered to depend on the MCP (or CEM) used, bias voltage, incident ion energy, incident angle, ionic charge, and the electronics used. We concluded that supplementally experiments on the ion counting efficiency under the same or similar conditions to those done in the photoionization experiments above were highly desirable. Our main interest lies on the single-ion counting by MCP at optimum bias voltages, but not in dc mode or counting at low bias voltages.

Because the counting efficiencies, either absolute or relative, depends on various experimental factors, it would be desirable that they are examined beforehand in each experiment. However, experiments where such preliminary procedures can be done are rather limited. Although the present study is motivated by the ion-detection problems in the limited photoionization experiments mentioned above, it would be of great interest for users of MCP to examine characteristics of a given MCP and to know similarities and differences among various types of MCP.

The experiment was carried out with \( \text{Li}^{q+}, \text{Ar}^{q+}, \text{Ba}^{p+} \) and \( \text{Yb}^{p+} \) \((q = 1, 2 \text{ and } p = 1, 2, 3)\) ions in two MCP-electronics combinations, MCP+Pre-Amp(E-output)+Amp(SCA) and MCP+Pre-Amp (T-output)+CFD. The difference between the two cases were found to be small. Consequently, results obtained in the former combination will be mainly reported.

2. Experimental

Fig. 1 shows schematically the experimental arrangement used for the measurement of the relative ion counting efficiencies. It is basically a magnetic deflection mass spectrometer consisting of an electron-impact ion source, a 60° sector magnet, and an ion-detection system composed of a suppressed Faraday cup C and an MCP. The mass analysis is done in the horizontal plane. The figure also shows the relevant electronics.

The Nier-type ion source employed can be operated for both gas targets and atomic beam targets. The target gas is admitted through a variable leak valve. When measurements are made for metallic ions, an oven placed below the ion source is operated. An electron-bombardment type oven is employed. This oven can provide atomic beams of metallic elements which require temperatures up
to about 2000 K for vaporization [18]. The energy of electrons impacting in the ion source was kept at 400–500 eV. At such high energies, ionization cross-section decreases to about one-third of the maximum value at lower energies. Nevertheless, such a high electron energy was used because results were obtained stably, as will be mentioned below.

The ions produced in the ion source are extracted and accelerated by a constant voltage $V_i$ (in most cases, 2.0 kV), mass analyzed, and then focused onto a vertical slit $S$. The slit $S$ is 1.5 mm wide and 8.0 mm long. A beam of selected ion species $A^{n+}$ then enters the suppressed Faraday cup, and its intensity is measured in dc mode. The Faraday cup has an incident-beam aperture of 10 mm $\times$ 10 mm, and can be moved horizontally along the direction normal to the ion beam with a linear motion feed through. The Faraday cup has a very thin slit of about 0.05 mm width and 6.0 mm length in its bottom plate. Its length direction lies in the horizontal plane. A very small constant fraction (about $10^{-3}$) of ions entering the Faraday cup passes through this slit, and enters the MCP placed at 22.5 cm downstream from the slit. Before entering the MCP, ions are accelerated additionally by a voltage $V_p$ between the grounded grid in front of the MCP and its input. The MCP used is of chevron-type double assembly (F1094-21S, Hamamatsu Photonics) and is specified by an effective detection diameter 20 mm, channel diameter 12 $\mu$m, channel length of one stage 0.48 mm, effective detection area about 60%, maximum bias voltage 1000 V for one stage and typical gain $5 \times 10^6$ at 1.9 kV bias voltage. Secondary electrons produced by each ion entering the MCP are multiplied and form a mass of cascade electrons which is converted into a negative pulse. The pulses thus produced, after passing through a Preamplifier (ORTEC 142B) and then an Amp/SCA module (ORTEC 590A) or a CFD module (ORTEC CF 4000), are counted.

In this paper, the relative detection efficiency $D_{q+}$ in single-ion counting mode (relative counting efficiency) for $A_{q+}$, ($q = 1, 2, \ldots$) ions as a function of the incident ion energy $E_K$ is defined as

$$D_{q+}(E_K) = (N_{q+})/I_{q+},$$  \hspace{1cm} (1)

where $N_{q+}$ is the counting rate in c/s, and $I_{q+}$ is the current of the incident ion beam collected by the
Faraday cup. The incident ion energy $E_K$ is determined by the total ion-acceleration voltage $V_a$ ($= V_1 + V_2$). The absolute measurement of the counting efficiency requires knowledge of both (a) the ion-beam profile at the Faraday cup and (b) the fraction of the ions passing through the bottom slit of the Faraday cup. In the relative efficiency measurement, it should be essential that the constancy of (a) and (b) is ensured regardless of ionic species.

It is then necessary in the present study to repeat preliminary measurements on selected ionic species under various ion-source and mass analyzer conditions and find the range where the constancy of (a) and (b) is well established. The exit slit of the ion source and the slit $S$ after mass analysis are set vertically. On the other hand, the ion source is constructed so that the beam adjustment is possible only in the horizontal direction. The beam adjustment in the vertical direction can be made through the position adjustment of the analyzing magnet. The position of the analyzing magnet was first adjusted so that, when the magnetic field was scanned, the ion-beam intensities at the Faraday cup and the MCP attained maxima at the same time. Then we made the preliminary measurements of $D_{q+}$ curves for Ar$q^+$ ($q = 1, 2$) and Ba$q^+$ ($q = 1, 2, 3$) ions repeatedly while changing the ion-source parameters. From these preliminary measurements, we found that the constancy was ensured if we used an electron-impacting energy as high as possible and an appropriately stronger ion-extraction field at a constant value of ion-acceleration voltage $V_a$.

The distance between the MCP and the Faraday cup was taken larger (22.5 cm). This widens the range where the depression of count rate due to finite charge recovery time of a stimulated channel does not occur. Fricke et al. [4] reported that the counting efficiency of CEM for H$^+$ and Ar$^+$ ions started to decrease around $1 \times 10^3$ c/s and declined to about 40% of the maximum value at $2 \times 10^4$ c/s. Such a decline may also occur in the MCP case if incident ions are concentrated to a small part of the front surface of the MCP. In the present study, the ion beam after mass selection has an angular spread of about 0.024 rad. This is rather fortunate because it makes the effective MCP area that the ions hit larger and hence makes the count rate at which the decline starts higher. In fact, in the present study, the counting efficiency was kept almost constant up to $8 \times 10^3$ c/s (see below).

In order to obtain reliable results using the present apparatus, other two conditions must be satisfied. First, the primary ion beam must be sufficiently intense to be measured correctly with a dc amplifier, but also sufficiently weak so that the depression of $D_{q+}$ (the counting loss) is negligible. This requirement was found to be fulfilled in the present setup with the primary ion-beam current of the order of $10^{-13}$-$10^{-12}$ A. An example showing satisfaction of this requirement is shown in Fig. 2. It indicates the relative counting efficiency $D_{q+}$ as a function of the count rate (c/s). It is found that the proposed condition is well satisfied up to $8 \times 10^3$ c/s. This count rate corresponds to an Ar$^+$ ion current of about $1.35 \times 10^{-12}$ A.

The second condition to be satisfied is that the angular spread of the ion beam after passing through the slit $S$ is within the acceptance angle of both the Faraday cup and the MCP. Fig. 3(a) shows the relative ion-beam intensity measured while moving the Faraday cup horizontally. The profile is a flat-topped and gives the full beam

![Fig. 2. The relative detection efficiency $D_{q+}$ as a function of count rate (c/s) obtained in the Pre-Amp(E-output)+Amp/SCA combination. The ionic species used was Ar$^+$. The count rate $10^5$ c/s corresponds, in this case, to Ar$^+$ ion current of about $1.7 \times 10^{-12}$ A measured by the Faraday cup.](image)
width of about 6 mm, indicating that the ion beam width is sufficiently narrower than that of the incident aperture of the Faraday cup. Fig. 3(b) indicates the profile of the ion beam entering MCP. It was determined by measuring the count rates while sliding horizontally a beam-shielding plate placed immediately in front of the MCP system, and by differentiating the count rates as a function of its position. The full width in the horizontal direction of the ion beam is estimated to be about 10 mm, also sufficiently narrower than its effective aperture (20 mm in diameter). The vertical width is at most 8 mm from geometrical considerations.

3. Results and discussion

3.1. Pulse height distribution

Previous studies have shown that pulse height distributions (PHD) for electron multipliers (MCP and SEM) depends on the kinetic energy $E_K$ (or velocity) and charge $q$ of incident ions [2,5]. This dependence comes originally from the difference in secondary electron emission at the input channel-wall of the multiplier. Hence, the examination of PHD is of fundamental importance to obtain the knowledge of gain characteristics of the MCP used and to set appropriately the discrimination level of the SCA.

Fig. 4 shows examples of PHD measured. The results in (a) and (b) are those obtained for $Ar^+$ and $Ba^{2+}$ ions, respectively, having different values of $E_K$, and the results in (c) and (d) for 2.0 keV $Ar^{q+}$ ($q = 1, 2$) (c) and 5.0 keV $Ba^{q+}$ ($q = 1, 2, 3$) (d) ions, respectively. All the results in Fig. 4 were obtained at bias voltage of 1.9 kV, the optimum bias voltage (see Section 3.2). All of the PHDs show peaked distribution. In (a) and (b), the peak positions of PHD are apparently different for different energies. In (c) and (d), however, the difference is very small. These results show apparently that the PHD is dominated by $E_K$ rather than $q$ at these energies. Although there is a literature saying that a peaked distribution is the result of saturation effect caused by space-charge limitation of secondary electron yield in the channels [19], the present result shows that the $E_K$ dependence of PHD still remain, and the “saturated distribution” is not reached at the bias voltage 1.9 kV. The saturated distribution here is defined as the distribution in which the shape and position of peaked PHD do not depend on $E_K$ and $q$ because of strong space-charge effect in the channel.

Here we review briefly the ion-induced secondary electron emission at a surface and consider the relation of it with PHD. Studies of this emission phenomenon date back to the 1950s [2,20]. The ion-induced electron emission can be described in terms of two different processes, kinetic emission and potential emission. The kinetic emission is due to kinetic energy transfer from ion
to a surface, and depends on ionic energy or velocity. The yield of secondary electrons due to the kinetic process is an increasing function of $E_K$ at least up to 50 keV [20]. The potential emission is due to the internal energy of ion, and hence depends on ionic charge. This process is independent of $E_K$ and dominates over the kinetic process at low incident energies up to a few hundred electron volts. The incident-ion energies in the present measurement covers from 1.1 to 15 keV. At such energies, the kinetic emission is expected to play main role.

As has been described above, the MCP in the present study is operated in the electron multiplication mode where the saturation of the PHD (saturated distribution) does not occur predominantly. In this range of electron multiplication, the average value of pulse height (called the average gain in the literature [2]) is nearly proportional to the average number $N_{av}$ of secondary electrons emitted at the input channel wall of MCP. Then, the results shown in Fig. 4 can be recognized as that the secondary electron emission depends largely on kinetic emission but only weakly on potential emission. However, as will be mentioned in Section 3.3, the difference in the secondary electron emission not always gives rise to the difference in the counting efficiencies once $N_{av}$ increases above some critical value.

In practical applications of MCP, we sometimes encounter cases where ions of different charges are detected after being accelerated by the same voltage. Fig. 5 shows, as examples in such cases, the PHD for Ar$^{p+}$ ($p = 1, 2$) and Ba$^{q+}$ ($q = 1, 2, 3$) ions.
accelerated by 5 keV. Apparently the peaked distribution shift to higher pulse height side with increase in $E_K$, indicating that the secondary electron emission at the MCP input is very different. This result can be expected easily from the results shown in Fig. 4 and will be helpful for understanding the results of the bias voltage dependence of $D_{q+}$ in Fig. 6(b).

When aiming at correct relative detection of ions with different charge, we have to set the discriminator levels of the SCA appropriately. The result of Figs. 4 and 5 indicate that the setting of the lower level of SCA at inappropriately high level causes counting loss of ions with lower charge. Also these results indicate that counting loss of ions with higher charge occurs if the upper level of SCA is set not appropriately or the amplifier is used with too high gain. In the present measurement, the SCA was used not in the gate mode but in the integral mode, so the upper level of the SCA was irrelevant.

3.2. Bias voltage dependence of $D_{q+}$

The bias voltage $V_B = V_{out} - V_{in}$, the potential difference between the voltage $V_{in}$ applied on the
input of MCP and the voltage $V_{\text{out}}$ on the output, is an important parameter, and should be applied appropriately. Fig. 6 shows two typical examples of the $V_{\text{B}}$ dependence of $D_{q^+}$, (a) one obtained for Ar$^+$ and Ar$^{2+}$ ions with the same values of $E_K$, 2.0 and 5.0 keV, and (b) one obtained for Ba$^{q^+}$ ($q = 1, 2, 3$) ions accelerated by the same value of $V_a$, 4.0 kV. All are measured in the Pre-Amp(E-output)+Amp/SCA combination. It is usually observed that, as $V_{\text{B}}$ increases, $D_{q^+}$ increases, starts to saturate, and comes to a constant value. Although the Ba curves show somewhat strange behavior, the $D_{q^+}$ versus $V_{\text{B}}$ curves for other elements studied are similar to the Ar curves. From these results as well as other ones not shown here, we found that the $D_{q^+}$ values in the saturated region ($V_{\text{B}} \geq 1.9$ kV) were different at lower values of $E_K$ and $q$, but tend to come to values in a very limited range at higher values of $E_K$ or $q$.

Table 1 lists normalized $D_{q^+}$ values obtained at $V_{\text{B}} = 1.9$ kV for selected ionic species Ar$^{q^+}$ and Ba$^{q^+}$. The normalization is done with respect to the $D_{q^+}$ value for 10 keV Ar$^{2+}$ ions. This measurement was done within a single measurement separately from those shown in Fig. 7. Statistical uncertainties in this measurement were within $\pm 2\%$. We see a tendency that efficiencies for Ba ions are slightly larger than those for Ar ions. It is not certain whether this trend is real or due to certain experimental effects. However, considering the statistical uncertainties in this measurement, we conclude that, for the MCP used, the saturated $D_{q^+}$ values in the higher $E_K$ range are very close to each other. On the basis of the result in Table 1, the $D_{q^+}$ versus $V_{\text{B}}$ curves in Fig. 6(a) and (b) are normalized to the respective highest value in the saturated region.

The difference in $D_{q^+}$ observed in Fig. 6(b) can easily be understood from the PHD results shown in Fig. 5(b). The PHD at a lower bias voltage will be such that the individual PHD curves in Fig. 5 collapse to the left side with roughly the same rate. The result shown in Fig. 6(b) corresponds to the procedure that we set a lower level for such a collapsed PHD and measure the areas surrounded by the vertical line of the lower level, the distribution curve and the baseline with increasing the bias voltage. We can see easily that higher charge provide larger area at lower values of $V_{\text{B}}$.

We found from these PHD results that the bias voltage of 1.90 kV and higher is appropriate to obtain the detection efficiency data of good quality.

Table 1

<table>
<thead>
<tr>
<th>Ionic species</th>
<th>$E_K$ (keV)</th>
<th>$D_{q^+}$/$D_{2+}$ (10 keV Ar$^{2+}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar$^+$</td>
<td>2.0</td>
<td>87</td>
</tr>
<tr>
<td>Ar$^{2+}$</td>
<td>2.0</td>
<td>97$^b$</td>
</tr>
<tr>
<td>Ar$^+$</td>
<td>5.0</td>
<td>97</td>
</tr>
<tr>
<td>Ar$^{2+}$</td>
<td>5.0</td>
<td>102</td>
</tr>
<tr>
<td>Ba$^+$</td>
<td>5.0</td>
<td>100</td>
</tr>
<tr>
<td>Ar$^{2+}$</td>
<td>10.0</td>
<td>104</td>
</tr>
<tr>
<td>Ba$^{2+}$</td>
<td>10.0</td>
<td>104</td>
</tr>
<tr>
<td>Ba$^{3+}$</td>
<td>15.0</td>
<td>103</td>
</tr>
</tbody>
</table>

$^a$ These values, except that with superscript (b), were obtained within a single measurement separately from those in Fig. 8 to avoid systematic errors due to the variation in the beam transportation. The statistical errors in this measurement were $\pm 2\%$.

$^b$ The value for 2.0 keV Ar$^{2+}$ ions includes additional systematic error of 5%. This is attributed to the beam transportation variation arising from a different ion-accelerating voltage (0.9 keV) in the ion source.
and with good reproduction. However, the bias voltage higher than 2.0 kV was not used because of increased possibility of discharge. We concluded that an optimum bias voltage was from 1.90 to 1.95 kV for the MCP used.

3.3. The incident ion-energy dependence of $D_{q^+}$

Previous papers [1,3] have reported that counting efficiencies $D_{q^+}$ for a given atomic species tends to lie on a unique curve if $D_{q^+}$ is plotted as a function of $E_K$. Such plots in the present case are shown in Fig. 7 where the normalized counting efficiencies $D_{q^+}$ for Li, Ar, Ba and Yb ions are plotted as a function of $E_K$. The normalization is based on the results listed in Table 1, and is done in the higher energy (plateau) region. Each solid line passing through experimental points is drawn arbitrarily.

We can see two marked features. First, as in the previous papers [1,3], the experimental points of $D_{q^+}$ for a given atomic species tend to lie on its own unique curve. We express this curve as $D_{q^+} = f_{q^+}(E_K)$. Each curve is such that, as $E_K$ increases, it increases steeply at the beginning, keeps going up with decreased slope, and approaches a constant value (plateau region). Second, the $D_{q^+}$ curve for lighter atom gets into the plateau region at lower kinetic energy. This indicates that the secondary electron emission is dominated by the momentum of the incident ion rather than its kinetic energy. These features are in qualitative agreement with the results reported by Roven [1] and Hellsing et al. [2].

In order to understand the behavior of the $D_{q^+}-E_K$ curves obtained, we consider that the counting efficiency $D_{q^+}$ depends indirectly on $E_K$ via the secondary electron emission at the input channel-wall of MCP. More quantitatively, $D_{q^+}$ depends on the number distribution of or the average number, $N_{av}$, of secondary electrons emitted by an ion, and the $N_{av}$ depends on $E_K$. Thus we obtain relations $D_{q^+} = f(N_{av})$ and $N_{av} = g_{q^+}(E_K)$. Combining these relations results in the relation $D_{q^+} = f_{q^+}(E_K)$ given above. The former function $f(N_{av})$ is determined by MCP used, applied voltage and relevant electronics, and is independent of incident ion. The function $g_{q^+}(E_K)$ depends on the combination of MCP material and ionic species and characterizes the $D_{q^+}-E_K$ curve. It is certain that, as $N_{av}$ increases, $D_{q^+}$ increases at the beginning, but approaches to a constant in the region where $N_{av}$ passes over a critical value. This statement is supported by the results shown in Figs. 4 and 5. For example, the PHIDs for Ba$^{2+}$ and Ba$^{3+}$ ions accelerated by 5 kV are apparently different (Fig. 5(b)) but their $D_{q^+}$ values at 10 and 15 keV, respectively, are almost the same (Fig. 6(b)).

Although the information about the $N_{av}$ as a function of $E_K$ in the present MCP material is not available, clues for it are available from the literatures. For example, results for singly charged alkali ions incident on an Ag–Mg surface show the yields $N_{av}$ amounting to 2–3.5 at 5 keV incident energy and to 4–5 at 10 keV [20]. Another example reporting secondary electron yield for Ar$^+$ ions incident on a KBr surface [21] shows values of about 3 at 1.0 keV and about 6 at 5.0 keV. The present MCP material has probably $N_{av}$ values of nearly the same or higher than those of the Ag–Mg and KBr surfaces. When $N_{av}$ increases to 4–5 or more, an ion incident on the effective area of MCP will produce a pulse with a probability of almost unity, and the difference in the number $N_{av}$ will not lead to the difference in the counting efficiency so appreciably. From the results shown in Figs. 5 and 6 and from the above discussion associated with them, we are able to understand why the $D_{q^+}-E_K$ curve for a given atomic species lies on a unique curve having a plateau in the higher energy range. This tendency of $D_{q^+}-E_K$ curve seems to be general for commercially available MCPs.

The unique curve may depend on the bias voltage $V_b$ and the electronics used. Fig. 8(a) shows the comparison of $D_{q^+}-E_K$ curves obtained for Ba$^{2+}$ ions with $V_b = 1.90$ kV and 1.95 kV. We see that, although a slight difference is observed in the lower energy region, the entire shape is almost identical. The $D_{q^+}$ values in the plateau region were also almost the same. Fig. 8(b) shows the $D_{q^+}-E_K$ curves obtained for Ar$^{2+}$ ions with Pre-Amp(E)+Amp/SCA combination and Pre-Amp(T)+CFD combination. The difference in the relative variation is very small, and the Pre-
Amp+CFD combination tends to enter a plateau region at a slightly higher kinetic energy. The Pre-Amp+CFD combination, however, provided $D_{q+}$ values 5–15% higher than those in Pre-Amp+ Amp/SCA combination, depending on the CFD level. The adjustment of the CFD level showed the existence of very small pulses evidently attributed to the incident ions. The higher $D_{q+}$ values observed are possibly due to the combined effect of very high pulse-pair resolution (<50 ns) of the CFD and secondary small daughter pulse formed immediately after the parent pulse by the ion feed back in the channel or in the region between the two MCP plates. In the present case, the quantitative comparison of the $D_{q+}$ values between the two combinations is considered to be meaningless, and hence the $D_{q+}$–$E_K$ curves in Fig. 8(b) are normalized in the plateau region.

4. Conclusion

We have studied the relative detection efficiencies of MCP in the counting mode (the relative counting efficiencies) at the optimum MCP condition for Li$^{q+}$, Ar$^{p+}$, Ba$^{p+}$ and Yb$^{p+}$ ($q = 1, 2$ and $p = 1, 2, 3$) ions with different kinetic energies. We summarize the present results as follows.

1. In the present incident ion-energy region (1.1–15 keV), the PHD is dominated mainly by the kinetic energy of ions (i.e. kinetic emission process) and little by their charge (i.e. potential emission process). This is the reason why the $D_{q+}$ as a function of $E_K$ for a given atomic species lies on its unique curve.

2. When ions of a given atomic species have different charge but the same kinetic energy, their counting efficiencies are almost the same as long as the kinetic energy is several keV or more. Almost equal detection efficiency is achieved at most at 4 keV for the ionic species studied.

3. When ions with different charges of a given atomic species are accelerated by the same voltage, there is a possibility that non-negligible differences occur for different charge. The problem often referred to is that the detection efficiency for singly charged ions might be different from that for doubly charged ions. Negligible difference in detection efficiencies for different charge is achieved at higher incident energies for heavier ions. For example, for Ar$^+$ and Ar$^{2+}$ ions, this is achieved at 5 kV, but for Ba$^+$ and Ba$^{2+}$ ions, about 10 kV is required.

4. When correct relative intensities among different charges are needed, it is highly recommended that the PHD is previously examined and the detection system is set to the optimum condition before measurement.
References