Absolute detection efficiencies of an ion-counting system with a channel-electron multiplier

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Abstract. Absolute detection efficiencies of an ion-counting system have been examined for Li+, Rb+, Cs+, Ar+, and Ar2+ ions as a function of the incident ion-impact energy. The ion-counting system consists of a converter plate (SUS), an electrostatic-lens system, and a channel-type secondary-electron-multiplier. For all ions examined in this study, the detection efficiencies are about unity if the ion energy is greater than 5 keV. The charge-state dependence is not as high for Ar+ and Ar2+.

1. Introduction
Ion detection in counting mode, using a channel-type secondary-electron-multiplier (CEM) or a microchannel plate (MCP), is commonly applied in ion–neutral-collision and photoabsorption experiments involving ions. In experiments where one requires the absolute number of ions produced, knowing the detector’s absolute detection efficiency is essential. Because the detection efficiency depends on the kinetic energy of the ions as well as their nature, it is important to examine the energy dependence of the absolute detection efficiency for various ions.

Several experimental studies of the ion-detection characteristics of CEMs or MCPs in counting mode have been reported. Burrous et al. [1] and Ravon [2] studied the relative detection efficiencies of a channeltron for several ions. Absolute detection efficiencies were studied by Iglesias and McGarity [3] for H+ of energy 0.2–10 keV, Crandall and Ray [4] for H+ and H– of 0.3–5 keV, and Fricke et al. [5] for H, He, Ar, Kr, and Xe ions above 4 keV. Using MCPs, relative detection efficiencies have been measured by Luhmann et al. [6] for Xeq+ (q = 1, 2, 3) and by Yagi et al. [7] for Li, Ar, Ba, and Yb ions. Takagi et al. [8] reported the gain characteristics of a CEM and an MCP for multiply charged ions.

The purpose of the present study was to examine the absolute ion-detection efficiency in single-ion counting mode by an ion-counting system using a CEM (Channeltron 4139S). This counting system is the same as the ion detector used for the absolute photoionization cross-section measurements of Xe+ [9]. The experiment was carried out with Li+, Rb+, Cs+, Ar+, and Ar2+ ions in the energy range from 0.2 to 6 keV.

2. Experimental set-up
Figure 1 shows a schematic diagram of an ion-counting system and the detection-efficiency measurement set-up. The ion-counting system consists of a converter plate (SUS), an electrostatic-lens system, and a CEM. A surface-ionization-type ion source was used for singly charged alkali ions and
an Electron Cyclotron Resonance ion source (NANOGAN) for Ar⁺ and Ar²⁺. The incident ions passing through a narrow slit in the bottom of a movable Faraday cup hit the converter plate and the secondary electrons emitted from the converter are subsequently accelerated to the CEM. The output signals from the CEM are counted using conventional ion-counting electronics. The Faraday cup has an incident-beam aperture diameter of 16 mm and can be moved vertically along the direction normal to the ion beam with a linear-motion feedthrough.

The absolute detection efficiency, \( D \), is defined as

\[
D = \frac{q e}{I_f} \int n(x) dx = \frac{q e}{I_f} \sum_i \frac{n(x_i)}{w} \Delta x ,
\]

where \( I_f \) is the ion current measured at the Faraday cup, \( x \) the position of the slit, \( n(x) \) the count rate from the CEM (counts s⁻¹; cps) at \( x \), \( x_i \) the \( i \)'th position of the slit, \( \Delta x \) the stepping distance of the slit, \( w \) the slit height, \( q \) the charge state, and \( e \) the elementary charge.

The total ion current, \( I_i \), was measured by an electrometer (Advantest TR8651) calibrated with a standard power supply and a standard resistor. The typical total primary ion-beam current in this set-up is in the order of \( 10^{-14} \) to \( 10^{-13} \) A. The slit in the bottom of the Faraday cup is 16 mm wide and 0.030 mm high. The FWHM of the measured primary-beam profile is typically 1.5 mm. A very small fraction of primary ions passes through the slit and then hits the converter plate. The secondary electrons emitted from the converter are accelerated and focused on the CEM by the lens system. The acceleration voltage between the converter and the CEM, and the CEM bias voltage (\( V_{\text{cin}} - V_{\text{cout}} \)) are fixed at 1.9 and 2.6 kV, respectively. These voltages represent the optimum condition for ion counting. A typical ion-count rate at the beam’s peak position is about \( 10^4 \) cps. The measurements were made at several count rates, from 8000 to 15000 cps. Because we do not observe any count-rate dependence in this experiment, we can neglect ion-count loss for count rates of this order. The stepping distance of the slit is normally 0.10 mm. We have examined the effect of using a smaller stepping distance (0.04 mm), but no stepping-distance dependence was observed.

The main origin of the systematic experimental error is the determination of the slit height and beam fluctuations during the measurements. The slit height is determined experimentally as

\[
w = \frac{1}{I_f} \sum_i I_c(x_i) \Delta x ,
\]

where \( I_c(x) \) is the ion current of the converter plate at the slit position, \( x \). In this measurement, \( I_c \) can be measured in direct-current mode, because \( I_f \) is in the order of \( 10^{-6} \) A. The slit height determined in
this experiment is 0.0308±0.002 mm. Fluctuations in the ion beam are about 1%. The total systematic error in the detection efficiency is estimated at about ±2%.

3. Results and discussion

Figure 2 shows a typical pulse-height distribution (PHD) from a main amplifier (ORTEC471) for Cs⁺ ions of different ion-impact energies. The bias voltage is fixed at 2.6 kV. All PHDs show peaked distributions. This is the result of saturation caused by the space-charge limitation of the secondary-electron yield in the channels. The peak positions of the PHDs do not depend on the ion-impact energy, except for the low-impact energy of 2.6 keV. The present result shows that the saturation distribution is reached at a bias voltage of 2.6 kV, except for the low-energy regime. It is necessary to set the discriminator level of a single-channel analyser (SCA: ORTEC 551) appropriately to obtain the correct detection efficiency. The results in Fig. 2 indicate that setting the discriminator level is not difficult for this system, and that any dark current or low-noise effect is negligible in this experiment.

Figures 3 and 4 show the absolute detection efficiencies, $D$, for alkali ions and for Ar⁺ and Ar²⁺, respectively, as a function of the ion-impact energy at the converter plate. Each point in the figures is the mean of several measurements. The estimated statistical uncertainties in this experiment were within ±2%.

$D$ increases with increasing ion energy and approaches a constant value in the higher-energy regime. For all ions examined in this study, $D$ is about unity if the ion energy is greater than 5 keV.

Fig. 2. Typical pulse-height distributions for Cs⁺ ions with different ion impact energies: (a) 2.6 keV, (b) 3.5 keV, and (c) 4.3 keV.

Fig. 3. Absolute detection efficiencies for Li⁺, Rb⁺, and Cs⁺ as a function of the ion-impact energy.

Fig. 4. Absolute detection efficiencies for Ar⁺ and Ar²⁺ as a function of the ion-impact energy.
According to the specifications of the channeltron used, its electron-detection efficiency has a peak value of 0.6–0.7 around 1 keV. To obtain $D = 1$, more than one electron must be emitted from the converter plate by the ion impact. The average number of secondary electrons emitted from the converter depends on the ion-impact energy. This is the origin of the energy dependence of $D$.

The charge-state dependence is not as high for Ar$^+$ and Ar$^{2+}$. $D$ depends only on the ion energy for a given atomic species. This feature is in qualitative agreement with the results of Ravon [2], Luhmann et al. [6], and Yagi et al. [7]. This means that the kinetic-emission mechanism dominates secondary-electron emission in this energy range.

In the lower-energy regime, $D$ not only depends on the ion energy but also on the atomic mass. Lighter atoms have a higher $D$ for the same ion energy. Burrous et al. [1] proposed an empirical universal proportionality relation, as in

$$D \propto m^{\alpha}v,$$  

where $v$ is the ion velocity, $m$ the atomic mass, and $\alpha = 0.4$. We obtained the same type of mass dependence, but with $\alpha = 0.48$, in this experiment.

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