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RAPID COMMUNICATION

New results on the absolute ion detection efficiencies of a microchannel plate

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Abstract. Absolute single-particle detection efficiencies and pulse height distributions of a cascaded microchannel plate (MCP) detector are reported for the ions H_2^+, Ne^+, Ar^+, Kr^+ and Xe^+ in the impact energy range 0–4.75 keV. The detection efficiencies have been obtained using the photoelectron–photoion coincidence (PEPICO) technique which allows the determination of detection efficiencies without knowledge of the absolute ionization rate. The mean gain is found to increase with increasing ion impact energy and decreasing ion mass. Depending on the ion mass, the absolute detection efficiencies saturate above 2.5 keV and reach about 63%.

Microchannel plates (MCPs) are frequently used in experimental research instrumentation systems for the detection of electromagnetic radiation and neutral and charged particles. One important MCP application has been in the detection of positive ions in many designs of mass or energy analysers. The absolute detection efficiencies of MCPs for ions are of particular interest if absolute intensities of particle currents are required or if the counting rates of different ions have to be related to each other. However, information on the detection efficiencies for particles is very limited (Fraser 1989). In a recent work that has been carried out in our laboratory (Brehm *et al* 1995), the absolute single-particle detection efficiencies of a MCP for ions were determined by using the photoelectron–photoion coincidence (PEPICO) technique (Brehm and von Puttkamer 1967). In the present work, we report on new and extended results for H_2^+ and rare gas ions obtained with an improved experimental set-up.

The PEPICO detection system has been described previously (Brehm *et al* 1995); however, some significant improvements have been made. Briefly, a light beam in the vacuum-ultraviolet region is produced by a gas discharge lamp. A monochromator (1 m McPherson) selects the desired wavelength and focuses the light beam onto the target beam effusing from a capillary array. Electrons and ions are produced by photoionization of the target atoms or molecules. A potential difference of 600 V between two parallel grids (numbers 1 and 2) produces a homogeneous electric field across the ionization volume and the charged particles are accelerated in opposite directions depending on the sign of their charge. After passing grid number 1, the electrons are finally accelerated to 670 eV before they strike the front side of a cascaded MCP detector (chevron). After their primary acceleration, the positive ions enter a field-free region between grid number 2 and a third grid which is held at the same potential as grid number 2. The length of the field-free region is twice the distance of the ionization volume to the primary acceleration grid. By this means, time-of-flight focusing is achieved, resulting in a considerable reduction of the time-of-flight widths which are typically 15 ns (full width at half maximum). After passing through the field-free region, the ions are accelerated by means of a fourth grid towards a second cascaded MCP detector (chevron). The ions hit the MCP surface at right angles and with impact energies in the range of 0–4.75 keV. The front side of the first MCP is biased at +50 V with respect to the final acceleration grid in order to drive electrons emitted from the interchannel web of the MCP back to the MCP (Brehm *et al* 1995). This electron back-driving field increases the relative detection efficiency from about 0.75 to 1.0. Each of the grids has a transmission of 78%. The electric charge pulses from the MCP detectors are fired into commonly used coincidental electronics. The electron pulses are used to start a time-to-amplitude converter; the ion pulses provide the stop signal. In this way, time-of-flight mass spectra are obtained. The time-of-flight differences are in the range 0.5–4.25 μs for the ion mass range 2–131 u. For calibration purposes, the ion pulses are preamplified by a charge-sensitive amplifier accounting for a pulse height analysis of

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the MCP output pulses. The vacuum conditions have also been improved. Among other things, the vessel containing the detection system is now evacuated by a turbomolecular pump that guarantees a vacuum nearly free of oil. Without running the gas beam, the background pressure is below 6×10^{-8} hPa, whereas with the gas beam the background pressure increases by a factor of 100.

The MCPs used are of type G12-36ST/15/T from Philips Photonics. These plates have 36 mm outer diameter, a channel diameter of 12.5 μm, a channel bias angle of 15°, a channel length-to-diameter ratio of 40:1 and an open area of at least 60%. The electrode at the input surface has been deposited half of the channel diameter into the channels whereas at the output surface the electrode penetration is about two channel diameters. The deep electrode deposition at the back side of the MCP is intended to lower the angular spread of the outgoing electrons (the focusing effect) because these MCPs are preferentially used for image-intensifier applications or position-sensitive particle detectors. Each MCP used for the ion detector is operated at 850 V.

The data evaluation procedure has been described by Brehm *et al* (1995). In short, the number of true coincidences $N_{coinc} = \epsilon_i \epsilon_e N_{tot}$ is taken from the time-of-flight mass spectra; ϵ_i and ϵ_e denote the effective detection efficiencies for the ions and electrons, respectively, and N_{tot} represents the total number of photoionization events. Together with the counting rate for the electrons $N_e = \epsilon_e N_{tot}$ and the subtraction of accidental coincidences N_{acci} and background electrons $N_{e,bg}$, the effective detection efficiency of the ions can be expressed as $\epsilon_i = (N_{coinc} - N_{acci})/(N_e - N_{e,bg})$. The effective detection efficiency is given by three contributions. (i) The ion collection probability T depends on the transmission of the three grids alone ($T = 0.78^3$) if both the geometrical arrangement and the applied electric fields ensure that all ions are guided to the MCPs. Saturation measurements as well as trajectory calculations prove that an electric field strength of 15 kV m^{-1} across the ionization volume is sufficient to collect all electrons and ions from the ionization volume. (ii) The pulse-height electronics needs discrimination against background pulses resulting from external sources and amplifier noise. So, real MCP pulses of small charge are cut off. From the analysis of the pulse-height distributions of the MCPs and the pulse processing of the discriminator unit, the pulse detection probability D is obtained. (iii) The absolute detection efficiency P_i of the MCP for ions which is the subject of the present work. Hence, the effective detection efficiency is given by $\epsilon_i = TDP_i$ and the following equation is used for the actual data evaluation:

$$P_i = \frac{N_{coinc} - N_{acci}}{N_e - N_{e,bg}} \frac{1}{TD}.$$

It has to be noted that the absolute detection efficiency is given by measured quantities only; knowledge of the absolute event rates is not required. Possible sources of error and their elimination have been discussed by Brehm *et al* (1995).

Figure 1 shows the pulse height distributions for H_2^+, Ne^+, Ar^+, Kr^+ and Xe^+ at the two selected impact energies 1 keV (left-hand column) and 4.5 keV (right-hand column), respectively. The abscissa has been calibrated with respect to the absolute number of output electrons. For each distribution, the dark-pulse distribution is obtained with the gas beam off and diffuse gas inlet at the same residual pressure. This signal is subtracted from the distributions measured with the target beam on. The dark count rises significantly below 0.2×10^7 output electrons. In figure 1, the vertical lines at 0.24×10^7 indicate the setting of the discriminator level. Charge pulses below that level are cut off and are not detected if time-of-flight mass spectra are recorded (see above). With increasing impact energy, the peaked pulse height distributions become broader. The maximum position, namely the modal gain of the MCP stack, and the centre of gravity, namely the mean gain (mean output charge) of the MCP stack, are shifted towards higher charge quantities. A striking observation is the double-peaked pulse height distribution for H_2^+ at an impact energy of 4.5 keV. At present, there is no confirmed explanation of the significance of this structure. If real, this observation requires further study.

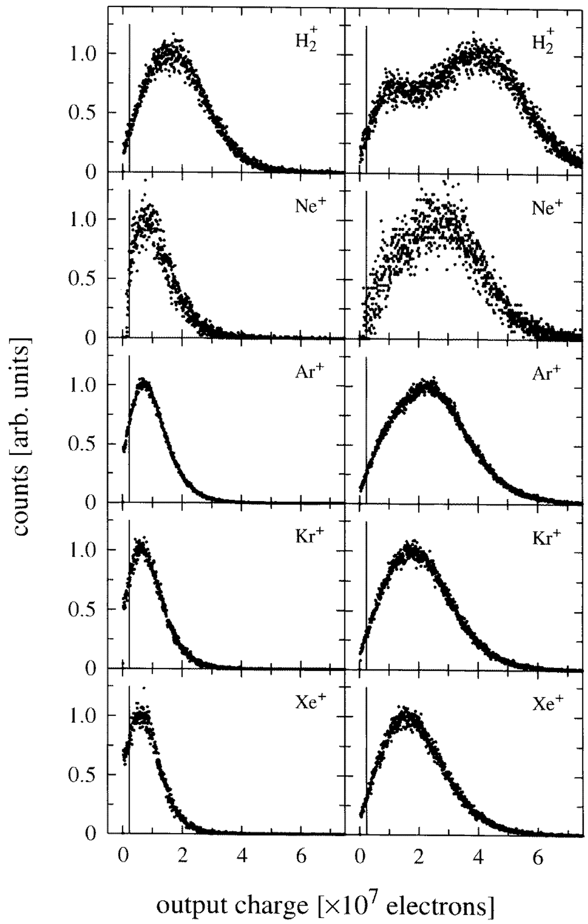

Figure 1. The pulse height distributions of the MCP stack at ion impact energy of 1 keV (left-hand column) and 4.5 keV (right-hand column). The abscissa has been calibrated with respect to the absolute number of output electrons. The MCP stack has been operated with 850 V per MCP. The vertical lines at 0.24×10^7 indicate the setting of the discriminator level (see text).

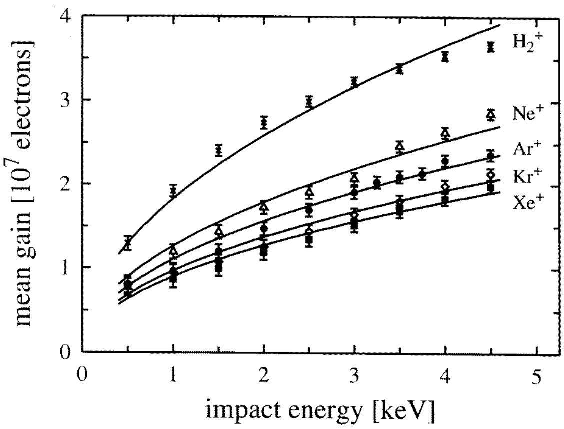

Figure 2. The mean gain (mean output charge) of the MCP stack for the ions under investigation as a function of the ion impact energy at an operating voltage of 850 V per MCP. The full lines show fits of the Parilis–Kishinevskii relation to our data (see text).

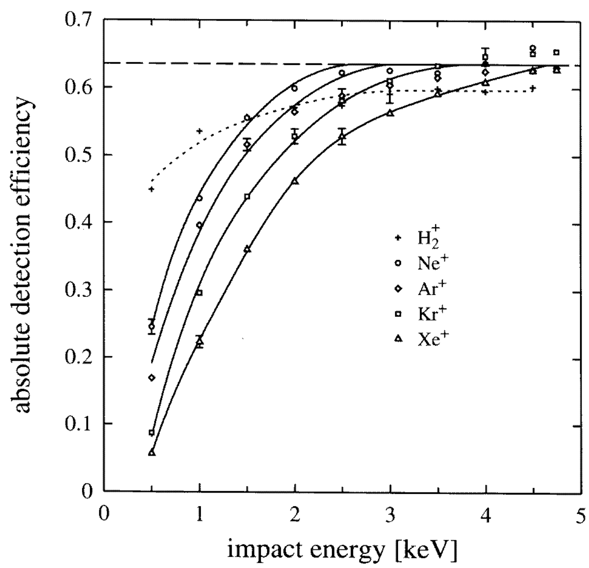

Figure 3. The absolute detection efficiencies of the MCP as functions of the ion impact energy. For the rare gas ions under investigation, the broken line shows the saturation of the absolute detection efficiencies at 63.5%.

In figure 2, the mean gain is plotted as a function of the ion impact energy. Since the ion-induced electron emission yield increases with ion velocity (Higatsberger *et al* 1954, Parilis and Kishinevskii 1960, Hellsing *et al* 1985), both the modal gain and the mean gain should be affected by the total number of initially produced electrons (Brehm *et al* 1995) which was confirmed by our experiment. This observation had already been made by Meier and Eberhardt (1993) when they investigated the gain of MCPs for different ions. Those authors successfully described the velocity dependence of their data in terms of the Parilis–Kishinevskii relation (Parilis and Kishinevskii 1960) which approximates the ion-induced electron emission yield by $av\tan^{-1}[b(v - v_0)]$ where the coefficients a and b are characteristic for each ion species. For ion velocities v much larger than the threshold velocity v_0, the relation becomes linear and the electron yield depends on the impact energy E of an ion with mass m as $(E/m)^{1/2}$. The full lines in figure 2 show fits of the Parilis–Kishinevskii relation to our data. Obviously, this relation describes the velocity dependence of the mean gain in a reliable way. For the rare gas ions, the mass dependence of the mean gain at fixed impact energies is described very well by the Parilis–Kishinevskii relation.

The absolute detection efficiencies P_i as functions of the ion impact energies are shown in figure 3. The indicated error bars represent two standard deviations as calculated from the statistical uncertainty of the counting rates plus the error in determining the pulse detection probability D. For the rare gas ions under investigation, the absolute detection efficiency increases from a threshold of around 0.5 keV to a more or less constant detection efficiency of $63.5 \pm 1.5\%$ which is close to the open area of the MCPs. The maximum absolute detection efficiency for H_2^+ has been found to be $59.7 \pm 1.4\%$. As pointed out in the previous work (Brehm *et al* 1995), the detection efficiency of a MCP should be ruled essentially by the initial detection efficiency for the incoming particles. If the ion-induced electron emission yield rises with increasing impact velocity and if it reaches such high values that the probability for no electron emission is reduced to negligible values, then the onset of the saturation is shifted to higher impact energies with increasing ion mass. This behaviour can be seen from figure 3. The absolute detection efficiencies are found to be independent of the total rate of ionization events given by the light beam intensity, the target beam density and the photoionization cross section. Different operating voltages of the MCPs entail a variation in the pulse height spectra but no change in the absolute detection efficiencies. This observation supports the assumption that the absolute detection efficiency is mainly given by the initial detection efficiency of the incoming particles. Several MCPs of the same type show identical absolute detection efficiencies.

The asymptotic values of the absolute detection efficiencies can be understood from trajectory calculations of the initially produced secondary electrons and their yields. In the case of Ar^+ ions with 3 keV impact energy, the secondary electron yield for the Nichrome-coated interchannel web is about 2.3 (Higatsberger *et al* 1954) and that for MCP material is around 5 (Hellsing *et al* 1985). If we assume for simplicity a Poisson distribution of the number of secondary electrons, then the probabilities for the emission of electrons are close to unity when an ion strikes the interchannel web or the open area. The electron-induced secondary electron yields are considerably lower. From the present operating conditions of the MCP, we estimate an electron impact energy of about 50 eV inside a channel. The same value can be taken for those electrons that are driven back due to the bias voltage between grid number 4 and the front side of the first MCP (see above). No published data have been found for Nichrome; limited data for nickel (Weast 1987) indicate a yield far below 1 for 50 eV electrons which gives a very low secondary electron emission probability. The electron-induced secondary-electron yield from reduced lead glass (MCP material) is about 1.5 (Authinarayanan and Dudding 1976) for 50 eV electrons which gives a high secondary electron emission probability. If no electron back-driving field is applied in front of the MCP, electrons from the interchannel web as well as electrons from the entrances of the channels may be accelerated away from the MPC surface, leading to a decrease in the detection efficiency. With increasing strength of the electron back-driving field more and more of these electrons are driven back to the MCP. Under the present operating conditions, most of these electrons hit the MCP very close to their origin; that is, electrons from the interchannel web strike the interchannel web again and vice versa. Hence, significant contributions to the development of an electron avalanche inside a channel come from ions striking the open area which approximately gives the maximum detection efficiency of the MCP.

When the MCPs are turned over so that the ions hit the back side of the MCP, then the absolute detection efficiencies are reduced to about 45%. This demonstrates the influence of the deeper electrode deposition on the absolute detection efficiency and can be qualitatively understood from the strongly different electron yields. At normal incidence to a 15° biased channel, ions and electrons will penetrate about 3.7 channel diameters. The lead glass fraction of the channels is very substantially decreased by electrode penetration of two channel diameters at the back side of the MCP. Consequently, we observe a substantial decrease in the absolute detection efficiencies. Because of the limited data, a quantitative analysis is hard to give at the present state of the experiments.

A direct comparison of the present results with the few other works on the absolute detection efficiencies of MCPs for ions (Brehm *et al* 1995) is rendered difficult, since the efficiencies depend on the details of construction of a MCP. However, the present results are in excellent agreement with the work of Gao *et al* (1984) who determined detection efficiencies of another type of MCP by comparing very low currents of H^+, O^+ and He^+ with the corresponding counting rates produced by the MCP detector.

It would be of great importance to determine the absolute detection efficiencies of various other ions and for other types of MCP used for physical applications. The constructional details of a MCP, for example the materials used for the MCP production, the electrode penetration into the channels, the open area, the channel bias angle or the ion impact angle, play an important role for the absolute detection efficiencies. These technical features may be improved for ion detection if detailed studies are performed. Besides that, the investigation of the distinctive properties of the H_2^+ pulse height distributions and their absolute detection efficiency (or those of other molecular ions) may give deeper insight into the physical processes operative in a MCP. Further work along these lines is under way and the results will be reported in a forthcoming publication.

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