



A compact high resolution electrospray ionization ion mobility spectrometer



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ARTICLE INFO

Article history:

Received 7 October 2015
Received in revised form
30 November 2015
Accepted 8 December 2015
Available online 10 December 2015

Keywords:

Ion mobility spectrometry
Electrospray
Water analysis
Three grid ion shutter

ABSTRACT

Electrospray is a commonly used ionization method for the analysis of liquids. An electrospray is a dispersed nebular of charged droplets produced under the influence of a strong electrical field. Subsequently, ions are produced in a complex process initiated by evaporation of neutral solvent molecules from these droplets. We coupled an electrospray ionization source to our previously described high resolution ion mobility spectrometer with 75 mm drift tube length and a drift voltage of 5 kV. When using a tritium source for chemical gas phase ionization, a resolving power of $R=100$ was reported for this setup. We replaced the tritium source and the field switching shutter by an electrospray needle, a desolvation region with variable length and a three-grid shutter for injecting ions into the drift region. Preliminary measurements with tetraalkylammonium halides show that the current configuration with the electrospray ionization source maintains the resolving power of $R=100$. In this work, we present the characterization of our setup. One major advantage of our setup is that the desolvation region can be heated separately from the drift region so that the temperature in the drift region stays at room temperature even up to desolvation region temperatures of 100 °C. We perform parametric studies for the investigation of the influence of temperature on solvent evaporation with different ratios of water and methanol in the solvent for different analyte substances. Furthermore, the setup is operated in negative mode and spectra of bentazon with different solvents are presented.

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1. Introduction

Ion mobility spectrometry (IMS) is a well-established technique for fast trace gas detection, offering limits of detection in the low ppt_v-range for measuring times of less than a second. The sensing principle of IMS is based on a separation of ions by their ion-specific mobility in a drift gas under the influence of an electric field [1]. Due to its analytical performance and comparably compact realization, it is attractive for a wide range of applications. IMS are commonly used for security applications such as the detection of chemical warfare agents [2,3], hazardous substances [4] or drugs of abuse [5]. However, today there exists a variety of other applications, e.g. in food industry [6] or medical applications [7,8]. For the analysis of liquids, a commonly used ionization method is electrospray ionization (ESI). In a fundamental work, Dole et al. first investigated electrospray ionization [9]. They showed that it is possible to produce ions in the gas phase from a dilute solution by electrospraying this solution. From the electrospray, little droplets are generated and subsequently solvent evaporation from these

droplets and repeated droplet fissions [10] result in charged analyte molecules. Based on these works, numerous setups with ESI-IMS were published and ESI-IMS is still a topic in recent research [11–15]. Application of ESI-IMS is found in aqueous nitrate and nitrite analysis, drug detection or detecting inorganic ions in water [16–19]. In the present work, we show a setup with a resolving power of $R=100$ using an only 75 mm long drift tube. As the desolvation region is thermally isolated from the drift tube, a parametric study for finding an optimal desolvation region temperature is performed. Furthermore, optimal solvent composition with focus on measuring aqueous samples is investigated.

2. Experimental

Fig. 1 depicts a schematic of the setup consisting of an emitter, a desolvation region, a drift region and a Faraday detector. New Objective Metal Taper Tip emitters with an inner diameter of 50 µm are used. Furthermore, we use a programmable syringe pump KDS LEGATO 100, KD scientific, USA with a 100 µl syringe (#1710) by Hamilton, Switzerland. For all our experiments, the flow rate is set in the realm of 0.5–1.5 µl/min. The ESI voltage is applied between emitter and the first ring of the desolvation region.

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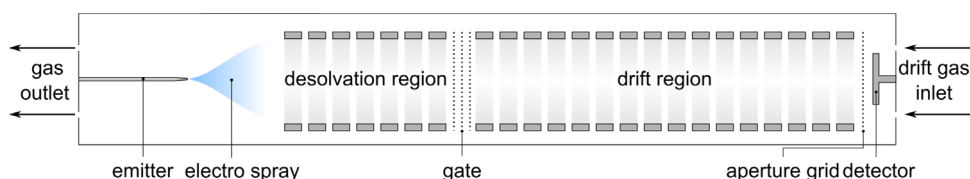


Fig. 1. Schematic of the ESI-IMS.

Generally, liquid samples are diluted with a solvent in order to support a stable electrospray and enhance the ionization process. One major task in electrospray ionization is the optimal evaporation of neutral solvent molecules. The length of the desolvation region in our setup is variable and can be extended up to a length of 75 mm. However, to ensure a complete desolvation, all experiments in this paper are performed with maximum desolvation region length. Furthermore, the desolvation region is equipped with four temperature controlled resistive heaters, MP9100, Cad-dock, USA and one temperature sensor, DS18B20, maxim integrated, USA, all mounted on an aluminum coat. In Section 3.2, the influence of the desolvation region temperature on the analytical performance is discussed in detail.

A three grid shutter first described in [20] separates the desolvation region from the drift region. The schematic of the three grid shutter is depicted in Fig. 2. The distance between the grids is 450 μm and is realized via PTFE spacers. When the switch is open, the voltage divider between the three grids sets the electrical field equal to the electrical field in drift region and desolvation region respectively. When the closing voltage $U_c = 75\text{ V}$ is applied, the direction of the electrical field between grid 1 and grid 2 is reversed. Thus, the ions are stopped from transmitting from the desolvation region to the drift region, while the electrical field in drift and desolvation region remains unchanged. The typical time ions are injected into the drift region is $t_{\text{inj}} = 175\text{ }\mu\text{s}$. The used drift tube design is described in [21]. Here, we use a tube with a drift length of 75 mm. The drift voltage of 4.9 kV is applied via a resistive voltage divider over stainless steel ring electrodes separated by PEEK isolation rings. Therefore, a homogeneous field inside the drift tube is realized. A faraday detector with aperture grid terminates the drift region. The drift tube and desolvation region are purged with the same gas flow of dry clean air at a flow rate of 250 ml/min. Table 1 summarizes the relevant operating parameters. Concluding this section, Fig. 3 depicts a photograph of the realized high resolution ESI-IMS to show the compact realization of the setup.

2.1. Chemicals

In this work the following chemicals are investigated: tetraethylammoniumiodide, ACS reagent, tetrapropylammoniumiodide, ACS reagent, tetrabutylammoniumiodide, ACS reagent, tetrahexylammoniumbromide, ACS reagent, tetraoctylammoniumbromide, ACS reagent, Triton X-100, [4-(1,1,3,3-Tetramethylbutyl)phenyl]-polyethylene glycol, t-Octylphenoxypolyethoxyethanol], Polyethylene glycol tert-octylphenyl ether, metalaxyl [N-(2,6-Dimethylphenyl)-N-(methoxyacetyl)-DL-alanine methyl ester], laboratory grade, carbamazepine [5H-Dibenz[b,f]azepine-5-carboxamide] and bentazon, analytical standard. All compounds were purchased from Sigma-Aldrich Chemie GmbH, Germany, except carbamazepine, which was generously provided by the group of Ursula Telgheder, University Duisburg-Essen. As solvents, methanol, HPLC grade, and acetonitrile, HPLC grade from CS-Chromatographie Service GmbH, Germany and ethanol, reagent ISO, reagent Ph. Eur. Sigma-Aldrich Chemie GmbH, Germany, are used. A solution containing 2 ppm of each tetraalkylammonium halide in ethanol and solutions of 50 $\mu\text{g/l}$ Triton X-100, 100 $\mu\text{g/l}$ metalaxyl, 500 $\mu\text{g/l}$ carbamazepine 500 $\mu\text{g/l}$ bentazon in pure

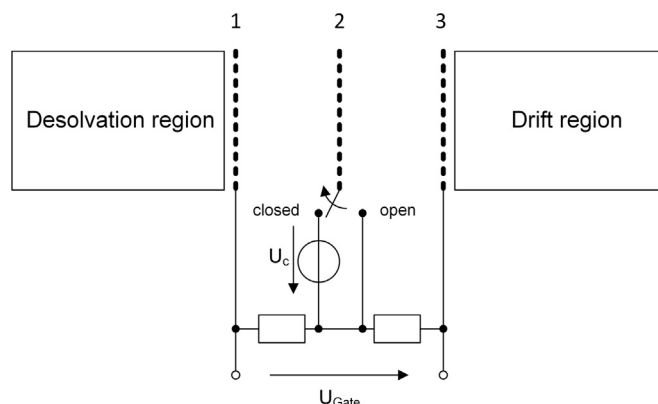


Fig. 2. Three grid shutter between desolvation and drift region.

Table 1
Operating parameter.

Length drift region (l_D)	75 mm	Dew point	$-85\text{ }^\circ\text{C}$
Length desolvation region	75 mm	Drift region temperature (T)	$23\text{ }^\circ\text{C}$
Drift voltage (U_D)	4.9 kV	Desolvation region temperature	$23\text{--}60\text{ }^\circ\text{C}$
Desolvation voltage (75 mm length)	5 kV	Ambient and inner IMS pressure (P)	1013 mbar
Emitter-to-ring voltage	2–2.8 kV	Liquid flow	0.5–1.5 $\mu\text{l/min}$
Drift gas flow	250 ml/min	Emitter diameter	50 μm
Desolvation gas flow	250 ml/min		

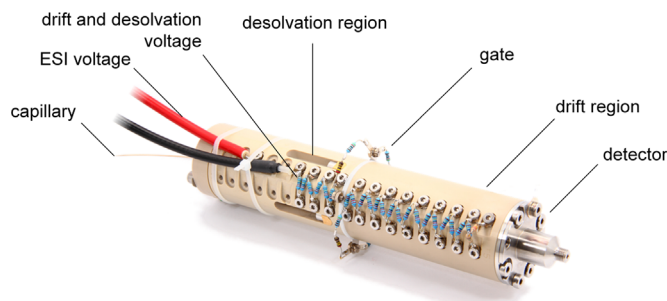


Fig. 3. Photo of the compact realization of the ESI-IMS.

methanol and mixtures of methanol and high purity water with different mixing ratios are prepared. Furthermore, for the analysis in negative mode, a solution of 500 $\mu\text{g/l}$ bentazon in pure acetonitrile and in mixtures of acetonitrile and high purity water are prepared.

3. Results and discussion

In this section, the setup is characterized in both positive and negative mode. Initially, the general performance of the setup is tested via measurements of tetraalkylammonium halides to determine the maximum resolving power that can be achieved. Subsequently, metalaxyl and carbamazepine are measured and the

influence of water content in the solvent is examined. With the equation given in [22], the reduced mobility K_0 of all compounds is calculated to

$$K_0 = \frac{l_D^2}{U_D t_D} \frac{P}{760} \frac{273}{T}$$

Here, l_D is the length of the drift region in cm, U_D is the drift voltage, P is the inner IMS pressure in Torr, T is the temperature in the drift region in Kelvin and t_D is the drift time of the peak in seconds. The reduced mobility corrects the influence of changing temperature and pressure on the neutral molecule density, which leads to a certain comparability between different setups. However, all other influences remain uncorrected and therefore different drift gases, clustering, adduct formation in ESI, and even temperature can still lead to completely different K_0 values for a single compound.

To facilitate an optimal desolvation of the solvent in the ionization process, the temperature of the desolvation region is varied and the influence on amplitude and resolving power is observed. Finally, the ESI-IMS is characterized in negative mode via measurements of bentazon in different solvents.

3.1. General performance

In a first step, the performance of the new shutter and drift tube combination is tested. Therefore, a mixture of 5 tetraalkylammonium halides in ethanol is measured. In [23], these compounds are proposed as instrument standards for ESI-IMS due to their low clustering tendency and their independence of electrospray performance. The spectrum of these compounds is shown in Fig. 4(a), the results are summarized in Table 2. Regarding the resolving power, confirms that replacing the tritium ionization source and field switching shutter by an ESI ionization source and three grid shutter has no negative impact on the performance of the instrument.

Having confirmed that the shutter [20] does not deteriorate the IMS performance, the complete system is tested with the polymer mixture Triton X-100 with an average molecular weight of 625 u. In [24] this compound, originally employed as detergent, is used to characterize an ESI-IMS setup with focus on high molecular weight compounds. Fig. 4(b) shows a spectrum of 50 µl/l Triton X-100 in methanol and the findings are found in Table 2. The results are consistent with the findings presented in [24]. In the spectrum, we achieve a baseline separation of the different polymers contained in the mixture due to the high resolution of our setup. Thus, our electrospray source efficiently ionizes the compound and furthermore, a good sensitivity and resolution for large

Table 2
Peak analysis.

Peak no.	Drift time (ms)	Reduced mobility K_0 (cm ² /Vs)	Resolution	SNR after 2s avg.
1	6.12	1.73	60	1219
2	7.37	1.44	77.4	1167
3	8.6	1.23	85.7	679
4	11.19	0.95	99.1	235
5	13.56	0.78	122.5	80
6	11.36	0.93	93.2	2
7	11.84	0.89	97.1	5
8	12.36	0.86	94.8	10
9	12.91	0.82	88.6	15
10	13.45	0.79	94	20
11	13.96	0.76	85.1	20
12	14.45	0.73	88.9	16
13	14.96	0.71	82.47	12
14	15.47	0.68	89.9	8
15	15.92	0.66	89.5	5
16	16.39	0.65	88.7	3

molecules can be estimated from this spectrum.

3.2. Characterization of the ESI-IMS in the positive mode

In this section, the influence of temperature on the electrospray ionization process is investigated for different mixing ratios of water and methanol in the solvent composition. Therefore, we use high purity water and methanol. The desolvation region is heated from outside with four temperature controlled resistive heaters, MP9100, Caddock, USA, mounted on an aluminum coat for a homogeneous temperature distribution. The temperature inside the desolvation region is monitored with a PT100 temperature sensor, GMH 3710, Greisinger, Germany. The distances between the three grids of the shutter are realized via PTFE spacers. PTFE has a very low thermal conductivity of 0.24 W/(m · K). Additionally, the drift gas cools the drift region via forced convection. Therefore, a good thermal isolation between drift and desolvation region is achieved. As the drift time of the peaks in the spectrum does not shift, even at desolvation region temperatures of up to 100 °C, it is concluded, that the temperature in the drift region stays at room temperature, regardless of changing the desolvation region temperature.

Fig. 5(a) depicts the desolvation region temperature dependent amplitude of 100 µg/l metalaxyl. Metalaxyl is a fungicide with a molecular weight of 279.33 u. Fig. 5(b) shows the temperature dependency of the amplitude of 500 µg/l carbamazepine. Carbamazepine is a medication e.g. used in the treatment of epilepsy. It

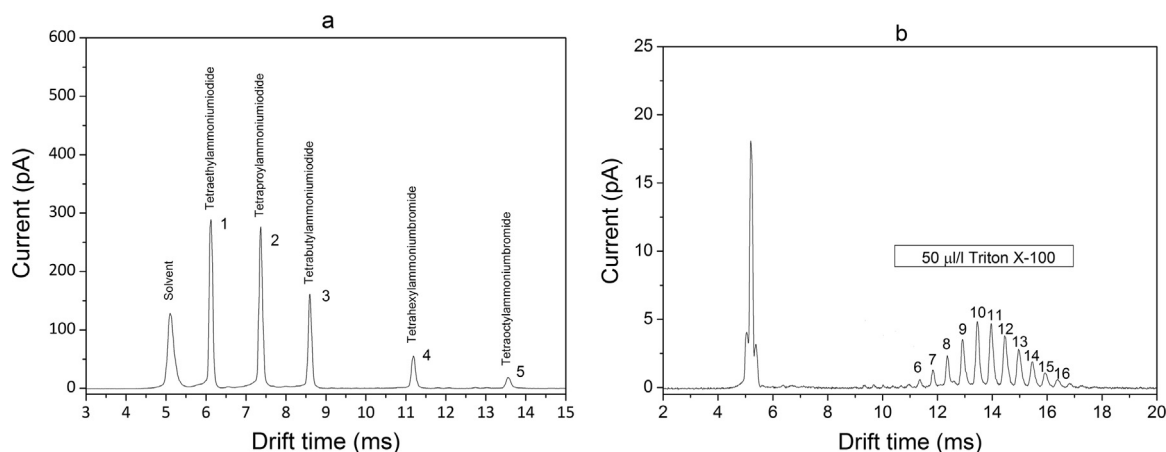


Fig. 4. Spectrum of 2ppm tetraalkylammonium halides in ethanol (a) and Spectrum of Triton X-100 in methanol (b).

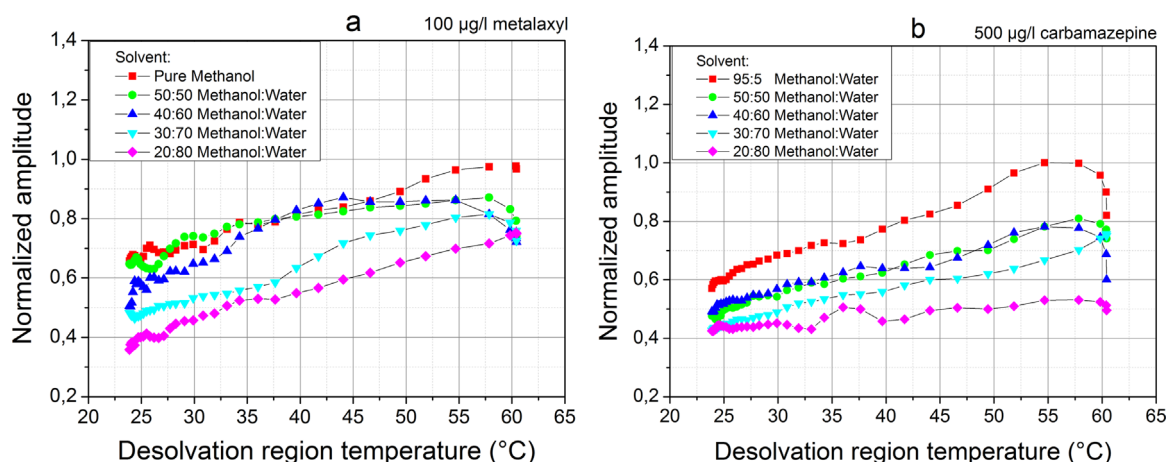


Fig. 5. Amplitude vs. desolvation region temperature (smoothed with five point savitzky golay) for metalaxyl (a) and carbamazepine (b).

as a molecular weight of 236.27 u. The reduced mobility of metalaxyl is calculated to $K_0 = 1.15 \text{ (cm}^2/\text{Vs)}$ and for carbamazepine to $K_0 = 1.22 \text{ (cm}^2/\text{Vs)}$. For the investigation of the temperature dependency for different solvent compositions, the analyte concentration is kept constant and the ratio of methanol to water is varied. At maximum water content of 80%, a stable spectrum could be achieved, but even higher water contents led to an unstable electrospray. As both analytes show similar behavior, it is concluded that the following observations are solvent specific and should therefore be applicable to other analytes. A higher water content in the solvent causes a smaller amplitude in the spectrum. However, increasing temperature in the desolvation region leads to higher amplitudes in the spectrum up to a temperature of about 55 °C. The more efficient ionization can be explained by an improved solvent evaporation, as it is a key factor in the mechanism of electrospray ionization [25]. When the temperature in the desolvation region is further increased towards the boiling point of methanol (65 °C), the baseline of the spectrum is lifted up and a multitude of additional peaks can be observed. A sound explanation for the additional peaks is found in [14]. At higher temperatures, these peaks can occur as a result from multiple charged solvent clusters. Furthermore, solvent evaporation inside the ESI emitter results in unstable electrospray conditions as shown in [26]. For the sake of simplicity, we chose to omit implementing needle cooling as proposed in [26]. Additionally, a comparably low ESI flow rate leads to the assumption that the ESI emitter is at the same temperature as the desolvation region, which explains a beginning evaporation above 55 °C desolvation region

temperature. Additional peaks in the spectrum, as well as unstable electrospray conditions result in a decrease of the analyte amplitude, which can be observed towards higher temperatures in Fig. 5.

Beside the amplitude, which refers to the sensitivity of our setup, a second important parameter for characterizing the analytical performance is the resolving power defined as $R_p = t_D/w_{0.5}$, where $w_{0.5}$ is the peak width at half maximum and t_D the drift time. Fig. 6 depicts the desolvation region temperature dependent resolving power of 100 µg/l metalaxyl (a) and 500 µg/l carbamazepine (b) respectively. For temperatures up to 50 °C, both graphs show an almost constant resolving power between $R=70$ and $R=90$ in Fig. 6(a) and $R=80$ and $R=100$ in Fig. 6(b) respectively. As the desolvation temperature is further increased, there is a massive decrease in resolving power. As for the decrease of the amplitude, beginning solvent evaporation and solvent clustering is an explanation for the observed behavior. Therefore, the optimal operation temperature of the desolvation region in our instrument is 50 °C as it combines a maximum resolving power with increased sensitivity.

To support these findings, the limit of detection (LOD) for both compounds is determined with a desolvation region at room temperature and at the optimal temperature of 50 °C. The LOD is defined as three times the standard deviation (3σ) of the blank. For the determination of 3σ , we measured blank solution of all used solvents at different desolvation region temperatures and compared the results to the noise in the spectra. In all cases the noise is very similar. For the following calculations we use the

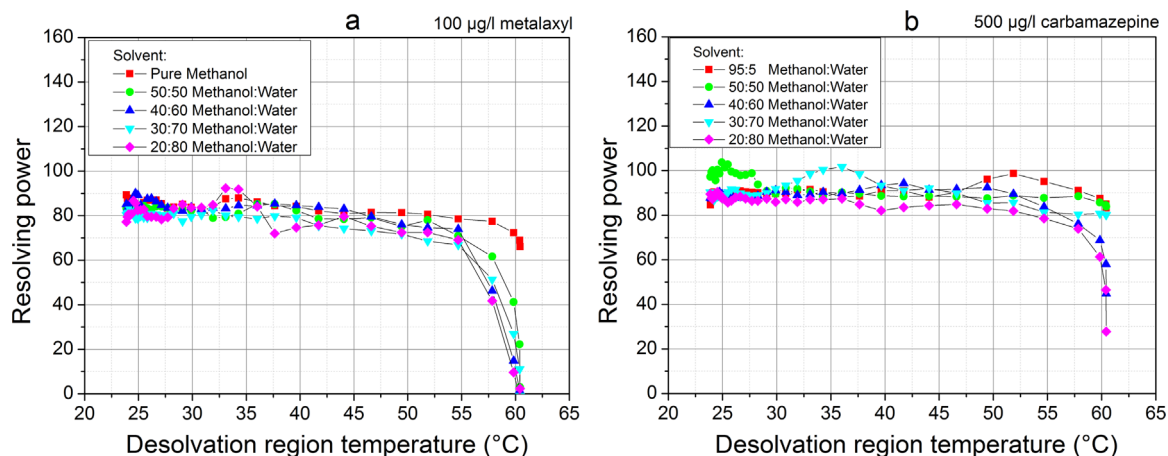


Fig. 6. Resolving power vs. desolvation region temperature (smoothed with five point savitzky golay) for metalaxyl (a) and carbamazepine (b).

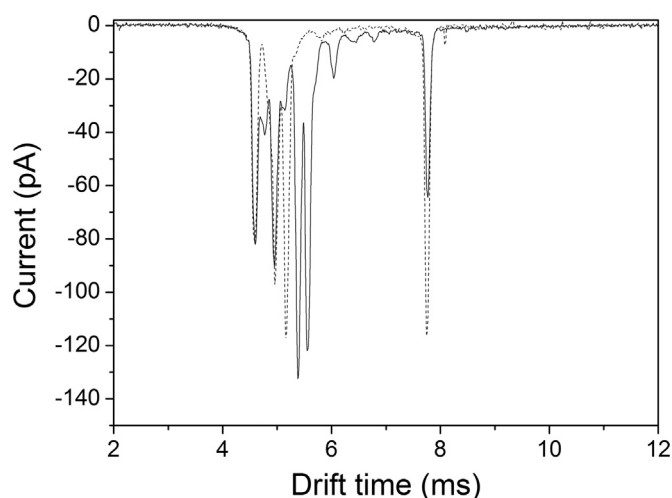


Fig. 7. Spectrum of 500 µg/l bentazon in methanol (straight) and acetonitrile (dashed) at 50 °C desolvation region temperature.

worst case noise of $3\sigma = 0.712$ pA after two seconds of averaging. For the determination of the concentration at 3σ peak height, a linear dependency between amplitude and concentration is assumed for low concentrations. Thus, the LOD for metalaxyl is derived to 37 µg/l at 23 °C and to 20 µg/l at 50 °C. Analogously, the LOD for carbamazepine is determined to 60 µg/l at 23 °C and to 34 µg/l at 50 °C. The results show that an optimal temperature in the desolvation region has a massive beneficial impact on the LOD, as the LOD at optimal temperature is almost half of the LOD at room temperature.

3.3. Characterization of the ESI-IMS in the negative mode

In this section, the results from measurements in negative mode are presented. Here, the analyte is bentazon, an herbicide with a molecular weight of 240.28 u. Fig. 7 depicts a spectrum of 500 µg/l bentazon in methanol (straight) and acetonitrile (dashed). The desolvation region temperature is set to the previously determined optimal temperature of 50 °C. The bentazon peak is found at a drift time of 7.77 ms, which leads to a $K_0 = 1.36$ (cm²/Vs).

Even small amounts of water added to methanol in the solvent composition resulted in an unstable electrospray. A similar observation is described in [27]. Here it is shown that addition of water to methanol leads to a massive decrease in signal amplitude and additionally facilitates the formation of corona discharge and therefore suppresses true electrospray ionization. However, using acetonitrile as solvent, we could increase the water content to 50%. Furthermore, ionization of bentazon in pure acetonitrile seems more efficient as the amplitude is doubled compared to bentazon in pure methanol as shown in Fig. 7. Analogous to the procedure in Section 3.2, the LODs are determined after 2 seconds of averaging. Using pure methanol as solvent results in an LOD of 6 µg/l. A solvent comprised of 50% water and 50% acetonitrile leads to an LOD of 8 µg/l, and from the measurement using pure acetonitrile as solvent an LOD of 3 µg/l can be derived.

4. Conclusion

In this paper, a compact ESI-IMS is presented and characterized. The ESI-IMS consists of a 75 mm desolvation region and a 75 mm drift region coupled via a three grid shutter. Measurements with tetraalkylammonium halides show that the same high resolving power can be achieved which was reported using a tritium source with the same type of drift tube. The desolvation region of

the ESI-IMS can be heated separately from the drift region as an additional advantage of the shutter is a good thermal isolation. Observation of the amplitude and resolving power of the analyte peak at different desolvation region temperatures revealed an optimal temperature of 50 °C. At this temperature, the LOD could be reduced almost by a factor of two compared to operation at room temperature, without any loss of resolving power. This effect was demonstrated via measurements of metalaxyl and carbamazepine. Additionally, the effect of water content in the solvent was investigated. We could achieve a stable electrospray even at a water content of 80% in positive mode. Finally, the setup was characterized in negative mode with bentazon using different solvents. Methanol with added water appeared to produce only unstable electrospray. However, using acetonitrile, up to 50% water could be added and still a stable electrospray could be achieved.

References

- [1] G.A. Eiceman, Z. Karpas, H.H. Hill, *Ion mobility spectrometry*, 3rd edn., CRC Press, Boca Raton, 2013.
- [2] R.G. Ewing, D.A. Atkinson, G.A. Eiceman, G.J. Ewing, "A critical review of ion mobility spectrometry for the detection of explosives and explosive related compounds," vol. 54, no. 3, 2001, pp. 515–529.
- [3] C. Wu, W. E. Steiner, P. S. Tornatore, L. M. Matz, W. F. Siems, D. A. Atkinson, H. H. Hill, "Construction and characterization of a high-flow, high-resolution ion mobility spectrometer for detection of explosives after personnel portal sampling," vol. 57, no. 1, 2002, pp. 123–134.
- [4] G.A. Eiceman, A.P. Snyder, D.A. Blyth, Monitoring of airborne organic vapors using ion mobility spectrometry, *Int. J. Environ. Anal. Chem.* 38 (3) (1990) 415–425.
- [5] A.B. Kanu, H.H. Hill, Identity confirmation of drugs and explosives in ion mobility spectrometry using a secondary drift gas, *Talanta* 73 (4) (2007) 692–699.
- [6] W. Vautz, D. Zimmermann, M. Hartmann, J.I. Baumbach, J. Nolte, J. Jung, Ion mobility spectrometry for food quality and safety, *Food Addit. Contam.* 23 (11) (2006) 1064–1073.
- [7] M. Jünger, W. Vautz, M. Kuhns, L. Hofmann, S. Ulbricht, J.I. Baumbach, M. Quintel, T. Perl, Ion mobility spectrometry for microbial volatile organic compounds: a new identification tool for human pathogenic bacteria, *Appl. Microbiol. Biotechnol.* 93 (6) (2012) 2603–2614.
- [8] W. Vautz, J.I. Baumbach, M. Westhoff, K. Züchner, E.T.H. Carstens, T. Perl, Breath sampling control for medical application, *Int. J. Ion. Mobil. Spec.* 13 (1) (2010) 41–46.
- [9] M. Dole, Molecular beams of macroions, *J. Chem. Phys.* 49 (5) (1968) 2240.
- [10] P. Kebarle, U.H. Verkerk, Electrospray: from ions in solution to ions in the gas phase, what we know now, *Mass. Spectrom. Rev.* 28 (6) (2009) 898–917.
- [11] A. Kuklya, F. Uteschil, K. Kerpen, R. Marks, U. Telgheder, "Development of an electrospray-(63)Ni-differential ion mobility spectrometer for the analysis of aqueous samples," *Talanta*, vol. 120 (2014) pp. 173–180.
- [12] M.T. Jafari, Improved design for high resolution electrospray ionization ion mobility spectrometry, *Talanta* 77 (5) (2009) 1632–1639.
- [13] A. Sysoev, A. Adamov, J. Viidanoja, R.A. Ketola, R. Kostianen, T. Kotiaho, Development of an ion mobility spectrometer for use in an atmospheric pressure ionization ion mobility spectrometer/mass spectrometer instrument for fast screening analysis, *Rapid Commun. Mass. Spectrom.* 18 (24) (2004) 3131–3139.
- [14] L.M. Matz, W.E. Steiner, B.H. Clowers, H.H. Hill, Evaluation of micro-electrospray ionization with ion mobility spectrometry/mass spectrometry, *Int. J. Mass. Spectrom.* 213 (2002) 191–202.
- [15] C. Wu, W.F. Siems, G.R. Asbury, H.H. Hill, Electrospray ionization high-resolution ion mobility spectrometry-mass spectrometry, *Anal. Chem.* 70 (23) (1998) 4929–4938.
- [16] H. Dion, L. Ackerman, H.H. Hill, Detection of inorganic ions from water by electrospray ionization-ion mobility spectrometry, *Talanta* 57 (6) (2002) 1161–1171.
- [17] K.M. Roscioli, J.A. Tufariello, X. Zhang, S.X. Li, G.H. Goetz, G. Cheng, W.F. Siems, H.H. Hill, Desorption electrospray ionization (DESI) with atmospheric pressure ion mobility spectrometry for drug detection, *Analyst* 139 (7) (2014) 1740–1750.
- [18] E.O. Espinoza, N.C. Lindley, K.M. Gordon, J.A. Ekhoft, M.A. Kirms, Electrospray ionization mass spectrometric analysis of blood for differentiation of species, *Anal. Biochem.* 268 (2) (1999) 252–261.
- [19] P. Dwivedi, L.M. Matz, D.A. Atkinson, H.H. Hill, Electrospray ionization-ion mobility spectrometry: a rapid analytical method for aqueous nitrate and nitrite analysis, *Analyst* 129 (2) (2004) 139–144.
- [20] J. Langejuergen, M. Allers, J. Oermann, A. Kirk, S. Zimmermann, High kinetic energy ion mobility spectrometer: quantitative analysis of gas mixtures with ion mobility spectrometry, *Anal. Chem.* 86 (14) (2014) 7023–7032.
- [21] A.T. Kirk, M. Allers, P. Cochems, J. Langejuergen, S. Zimmermann, A compact

- high resolution ion mobility spectrometer for fast trace gas analysis, *Analyst* 138 (18) (2013) 5200–5207.
- [22] R. Fernández-Maestre, C.S. Harden, R.G. Ewing, C.L. Crawford, H.H. Hill, Chemical standards in ion mobility spectrometry, *Analyst* 135 (6) (2010) 1433–1442.
- [23] J. Viidanoja, A. Sysoev, A. Adamov, T. Kotiaho, “Tetraalkylammonium halides as chemical standards for positive electrospray ionization with ion mobility spectrometry/mass spectrometry,” vol. 19, no. 21, 2005, pp. 3051–3055, 16200656.
- [24] D. Wittmer, Y.H. Chen, B.K. Luckenbill, H.H. Hill, Electrospray ionization ion mobility spectrometry, *Anal. Chem.* 66 (14) (1994) 2348–2355.
- [25] N.B. Cech, C.G. Enke, Practical implications of some recent studies in electrospray ionization fundamentals, *Mass. Spectrom. Rev.* 20 (6) (2001) 362–387.
- [26] Y.H. Chen, H.H. Hill, D.P. Wittmer, Thermal effects on electrospray ionization ion mobility spectrometry, *Int. J. Mass. Spectrom. Ion. Process.* vol. 154 (1996) 1–13.
- [27] G. Reid Asbury, Herbert H. Hill Jr, Negative ion electrospray ionization ion mobility spectrometry, *Int. J. Ion. Mobil. Spectrom.* vol. 2 (1999) 1–8.