

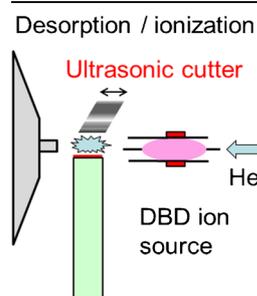
Desorption Mass Spectrometry for Nonvolatile Compounds Using an Ultrasonic Cutter

Ahsan Habib,¹ Satoshi Ninomiya,² Lee Chuin Chen,² Dilshadbek T. Usmanov,^{1,3} Kenzo Hiraoka¹

¹Clean Energy Research Center, University of Yamanashi, Kofu, 400-8511, Japan

²Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, 400-8511, Japan

³Institute of Ion-Plasma and Laser Technologies, 100125, Tashkent, Uzbekistan



Abstract. In this work, desorption of nonvolatile analytes induced by friction was studied. The nonvolatile compounds deposited on the perfluoroalkoxy substrate were gently touched by an ultrasonic cutter oscillating with a frequency of 40 kHz. The desorbed molecules were ionized by a dielectric barrier discharge (DBD) ion source. Efficient desorption of samples such as drugs, pharmaceuticals, amino acids, and explosives was observed. The limits of detection for these compounds were about 1 ng. Many compounds were detected in their protonated forms without undergoing significant fragmentation. When the DBD was off, no ions for the neutral samples could be detected, meaning that only desorption along with little ionization took place by the present technique.

Keywords: Tribology, Desorption, Friction, Sonication, Dielectric barrier discharge

Received: 20 December 2013/Revised: 19 March 2014/Accepted: 24 March 2014/Published online: 16 May 2014

Introduction

Tribological phenomena, observed at the interface of moving matter, are ubiquitous in nature even in the astrological physicochemical events in interstellar medium. The formation of negative ions in air when water splashes is known as the Lenard effect. The lightning in atmosphere is caused by charging via the friction of the water/ice particles in the clouds.

In mass spectrometry (MS), tribological phenomena also play important roles in desorption/ionization (e.g., sonic spray [1], neutral desorption by gas stream [2], solvent-assisted inlet ionization [3, 4], droplet impact ionization [5–9], acoustic wave nebulization [10–12], matrix-sublimation assisted ionization [13], desorption by solid-solid interface friction [14], etc.).

Friction is a dynamic process taking place between the contacting interfaces. A macroscopic force is exerted on the microscopic and nanoscopic scales at the friction interface and, thus, it is very difficult to obtain molecular-level information by the conventional analytical techniques [15].

In this respect, MS is highly appealing because it can provide molecular-level information by measurement of desorbed molecules and ions as described above. In this work, desorption of nonvolatile compounds deposited on a plastic substrate by using an ultrasonic cutter will be reported.

Experimental

The experimental system is shown in Supplementary Figure 1. The 2 μ L sample solution was deposited on the flat perfluoroalkoxy (PFA) substrate with 2 mm in diameter. After the liquid sample was dried in the air, the deposited sample was desorbed by touching the substrate very gently with an ultrasonic cutter (20 W, 40 kHz, oscillation amplitude: 16 μ m; Honda Electronics, Toyohashi, Japan). With this gentle touch, the surface of the substrate showed little damage as observed by the naked eye.

A fraction of the desorbed gaseous molecules was ionized by using a He dielectric barrier discharge (DBD) ion source (ARIOS, Akishima, Japan) [14]. In this ion source, the desorbed gaseous molecules were not exposed to the plasma but were ionized mainly by H_3O^+ and its water clusters $\text{H}_3\text{O}^+(\text{H}_2\text{O})_n$ produced outside of the DBD alumina tube [14]; that is, the present DBD ion source may be regarded as an APCI ion source. The temperature of effusing gas from

Electronic supplementary material The online version of this article (doi:10.1007/s13361-014-0899-7) contains supplementary material, which is available to authorized users.

Correspondence to: Kenzo Hiraoka; e-mail: hiraoka@yamanashi.ac.jp

the DBD ion source was 49°C. The slightly higher temperature than the room temperature is due to the radiofrequency heating of the dielectric tube. The low temperature gas flow is different than direct analysis in real time (DART), which uses a much higher gas temperature for sample desorption [16].

The ions generated by the DBD ion source were detected using an ion trap mass spectrometer (LTQ XL; Thermo Scientific, San Jose, CA, USA). The temperature of the ion transport tube was 125°C.

Results and Discussion

The present method was applied to several nonvolatile compounds. Figure 1a shows the mass spectrum of 2 ng cholesterol. The dehydrated peak is observed at m/z 369. Figure 1b presents the mass spectrum of 20 ng spinosad (insecticide). The protonated molecules at m/z 732 (spinosad A) and m/z 746 (spinosad D) in addition to the fragment ion from spinosad A and D at m/z 142 are observed. Figure 1c displays the urine containing 2 ng morphine. Morphine was detected in the protonated form without giving the dehydrated fragment ion at m/z 268 (see inset of Figure 1c). This indicated that under the present experimental conditions, the decomposition of morphine was negligible. The temperature rise during desorption seemed to be too low to cause thermal decomposition of morphine. In the mass spectrum for raw cow milk spiked with 2 ng melamine (Figure 1d), the appearance of the protonated melamine at m/z 127 as the base peak indicated that melamine in cow milk was

easily detected, and this was attributed to its high proton affinity (226.2 kcal/mol).

To obtain information on the mechanism of desorption, the thermometer molecule, p-chloro-benzyl pyridinium chloride, was examined. The result obtained for 100 ng of this compound without turning on the rf voltage of the DBD ion source is shown in Figure 2a. The chlorobenzyl pyridinium ion M^+ was observed as the base peak with a much weaker signal of the fragment ion $[M - \text{pyridine}]^+$ (i.e., p-chlorobenzyl cation, $\text{ClC}_6\text{H}_4\text{CH}_2^+$). The survival yield (SY) $I(M^+)/[I(M^+) + I(F^+)]$ was about 0.9, indicating that the larger part of thermometer molecules were desorbed without fragmentation under these experimental conditions. The ions at m/z 328 and 407 may be assigned to an adduct of the chlorobenzyl radical with M^+ , $[M + \text{CH}_2\text{C}_6\text{H}_4\text{Cl}]^+$, and its cluster with pyridine, $[328 + \text{pyridine}]^+$, respectively. This indicates that neutral pyridine molecules are produced by the dissociation of M^+ to $\text{ClC}_6\text{H}_4\text{CH}_2^+$ and $\text{C}_5\text{H}_5\text{N}$ during the rubbing process. In fact, the ion $[M - \text{pyridine}]^+$ is observed at m/z 125 in Figure 2a.

Figure 2b shows the mass spectrum obtained with rf voltage for the DBD ion source. The strong appearance of the protonated pyridine at m/z 80 clearly indicates the formation of pyridine by the fragmentation of M^+ . The SY of 0.95 in Figure 2b indicates that 5% of M^+ produced pyridine. The strong appearance of the protonated pyridine in Figure 2b is due to the high volatility of pyridine.

Supplementary Figure 2a shows the mass spectrum for glucose. The detection sensitivity for glucose was found to be low and more than 100 ng of the sample were necessary

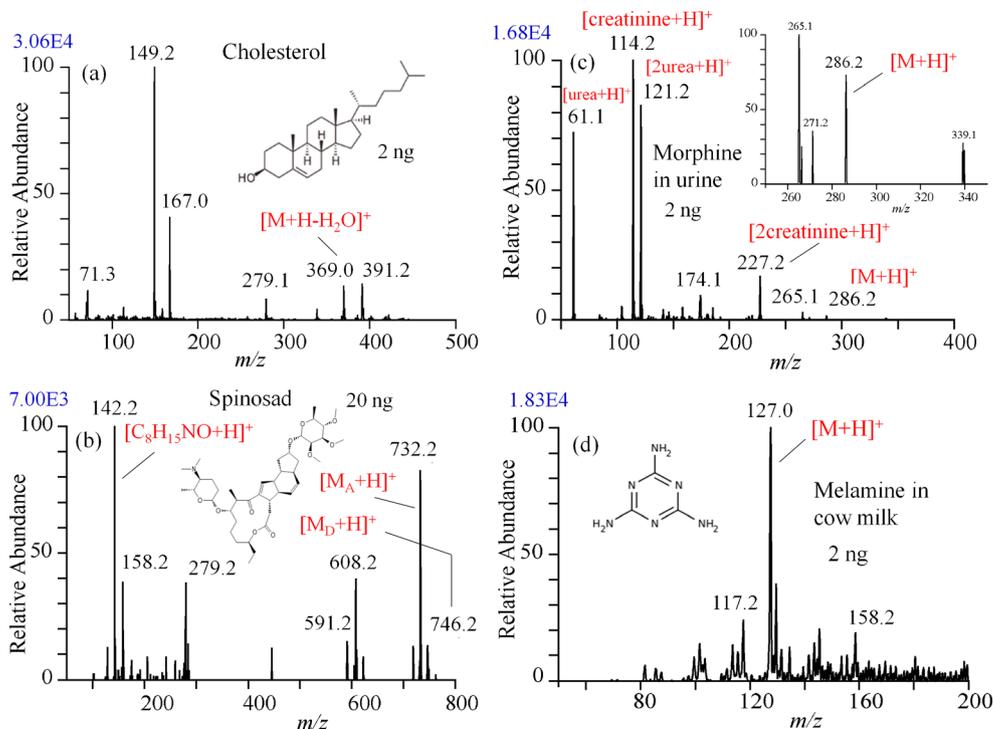


Figure 1. Mass spectra for (a) 2 ng cholesterol, (b) 20 ng spinosad, (c) dried 2 μL urine spiked with 2 ng morphine, and (d) dried 2 μL cow milk spiked with 2 ng melamine

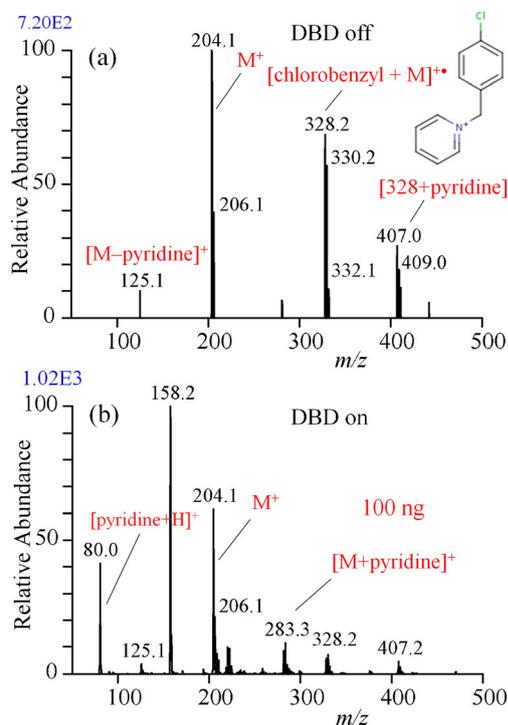


Figure 2. Mass spectra for 100 ng p-chloro-benzyl pyridinium chloride with DBD turned (a) off, and (b) on

to obtain reasonably strong ion signals. As in our previous work [14], the ions at m/z 163, 180, and 198 were observed. The ion at m/z 163 may be formed by the dehydration of protonated glucose, $[M+H-H_2O]^+$. To obtain information on the structures of ions at m/z 180 and 198, MS/MS was done for these ions. The ion at m/z 198 gave the ions at m/z 180 and 163. The ion at m/z 180 gave the ion at m/z 163. The elimination of the OH^\bullet radical from the ion at m/z 180 was highly unlikely because the fragmentation of sugar molecules proceeds mainly via molecular processes (e.g., dehydration) and the elimination of the OH^\bullet radical must be endothermic. It can be concluded that the dehydrated glucose $[M+H-H_2O]^+$ forms a cluster ion with NH_3 , present as a contaminant in the ambient air, to form $[M+H-H_2O+NH_3]^+$ at m/z 180.

Supplementary Figure 2b shows the mass spectrum for dried apple peel. In addition to signals originating from monosaccharide (m/z 163, 180, 198), ion signals originating from disaccharides (Hex_2) at m/z 325 $[Hex_2+H-H_2O]^+$, 342 $[Hex_2+H-H_2O+NH_3]^+$, and 360 $[342+H_2O]^+$ were observed. The tentative assignment of the peaks was made for disaccharides in Supplementary Figure 2b as the case of glucose in Supplementary Figure 2a.

Mazzotta et al. [17] analyzed ionic liquids by direct analysis in real time MS (DART-MS). They observed positive and negative ions for various ionic liquids with gas temperature of 400°C. Supplementary Figures 3a, b and 3c, d show the positive and negative-mode mass spectra of 200 ng of ionic liquids, 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide and tributylmethylammonium bis(trifluoromethylsulfonyl)imide, re-

spectively. It should be noted that these compounds gave no ion signals when DBD was off, indicating that these compounds desorb as neutral ionic pair as $(C^+A^-)_n$ with $n \geq 1$ and dissociate into positive and negative ions when exposed to the plasma-excited active gas downstream of the DBD ion source. In the figure, C^+ , A^- , their fragment ions, and cluster ions (C_2A^+ , CA_2^-) are observed. It is apparent that nonvolatile ionic liquids can be desorbed by the present technique.

In our previous work [14], C_{60} was examined by flash/desorption MS. The signal originating from C_{60} started to be observed at about 500°C and increased with temperature. In the present work, however, quantities of C_{60} from ng to μg , deposited and dried on the substrate did not give any ion signals. The absence of ion signals from C_{60} suggested that the temperature at the interface is much lower than 500°C. Deguchi et al. [18] discovered that rubbing bulk solids of C_{60} between two glass slides or finger tips generated nanoparticles consisting of approximately 2500 C_{60} molecules. They found that the frictional resistance of C_{60} increased progressively as it was rubbed, and coarse black particles eventually turned to a fine brownish powder and adhered to the glass slide surface. Our experiments show that mechanical rubbing is not an efficient method for desorption for C_{60} unless the substrate temperature is above 500°C.

The LODs for the compounds examined in this work are summarized in Supplementary Table 1.

Conclusion

In this work, desorption of nonvolatile compounds was investigated by using an ultrasonic cutter that was pressed softly against the flat surface of the plastic substrate. Because all the nonvolatile compounds except for C_{60} were desorbed with little thermal decomposition (e.g., morphine), the soft mechanical friction can be an efficient desorption method for nonvolatile compounds. The present technique is reasonably sensitive and may be applied for quick analysis of contaminants, such as narcotics, insecticides, explosives etc., deposited on solid surfaces. Further investigation to clarify the mechanism of friction-induced desorption is in progress in our laboratory.

Acknowledgments

The authors acknowledge support for this work by the Japanese Science and Technology. They thank Professor Zoltan Takats of the Imperial College of London for the illuminating discussion.

References

- Hirabayashi, A., Sakairi, M., Koizumi, H.: Sonic spray mass spectrometry. *Anal. Chem.* **67**, 2878–2882 (1995)
- Chen, H., Yang, S., Wortmann, A., Zenobi, R.: Neutral desorption sampling of living objects for rapid analysis by extractive electrospray

- ionization mass spectrometry. *Angew. Chem. Int. Ed.* **46**, 7591–7594 (2007)
- Zilch, L.W., Maze, J.T., Smith, J.W., Ewing, G.E., Jarrold, M.F.: Charge separation in the aerodynamic breakup of micrometer-sized water droplets. *J. Phys. Chem. A* **112**, 13352–13363 (2008)
 - Pagnotti, V.S., Chubatyi, N.D., McEwen, C.N.: Solvent assisted inlet ionization: an ultrasensitive new liquid introduction ionization method for mass spectrometry. *Anal. Chem.* **83**, 3981–3985 (2011)
 - Dubov, D.Y., Vostrikov, A.A.: Collision induced electrification of large water clusters. *J. Aerosol Sci.* **22**(Suppl. 1), S245–S248 (1991)
 - Mahoney, J.F., Perel, J., Ruatta, S.A., Martino, P.A., Husain, S., Lee, T.D.: Massive cluster impact mass spectrometry: a new desorption method for the analysis of large biomolecules. *Rapid Commun. Mass Spectrom.* **5**, 441–445 (1991)
 - Aksyonov, S.A., Williams, P.: Impact desolvation of electrosprayed microdroplets—a new ionization method for mass spectrometry of large biomolecules. *Rapid Commun. Mass Spectrom.* **15**, 2001–2006 (2001)
 - Hiraoka, K., Asakawa, D., Fujimaki, S., Takamizawa, A., Mori, K.: Electrosprayed droplet impact/secondary ion mass spectrometry. *Eur. Phys. J. D* **38**, 225–229 (2006)
 - Hiraoka, K., Ed.: Chapter 10: Cluster SIMS. In: Hiraoka, K. (ed.) *Fundamentals of Mass Spectrometry*, p. 199. Springer, New York (2013)
 - Dixon, R.B., Sampson, J.S., Muddiman, D.C.: Generation of multiply charged peptides and proteins by radio frequency acoustic desorption and ionization for mass spectrometric detection. *J. Am. Soc. Mass Spectrom.* **20**, 597–600 (2009)
 - Zhu, L., Gamez, G., Chen, H., Chingin, K., Zenobi, R.: Rapid detection of melamine in untreated milk and wheat gluten by ultrasound-assisted extractive electrospray ionization mass spectrometry (EEESI-MS). *Chem. Commun.* 559–561 (2009)
 - Heron, S., Wilson, R., Shaffer, S.A., Goodlett, D.R., Cooper, J.M.: Surface acoustic wave nebulization of peptides as a microfluidic interface for mass spectrometry. *Anal. Chem.* **82**, 3985–3989 (2010)
 - Chakrabarty, S., Pagnotti, V.S., Inutan, E.D., Trimpin, S., McEwen, C.N.: A new matrix assisted ionization methods for the analysis of nonvolatile compounds by atmospheric probe mass spectrometry. *J. Am. Soc. Mass Spectrom.* **24**, 1102–1107 (2013)
 - Usmanov, D.T., Ninomiya, S., Hiraoka, K.: Flash desorption/mass spectrometry for the analysis of less- and nonvolatile samples using a linearly driven heated metal filament. *J. Am. Soc. Mass Spectrom.* **24**, 1727–1735 (2013)
 - Nevshupa, R.A.: The role of athermal mechanisms in the activation of tribodesorption and triboluminescence in miniature and lightly loaded friction unit. *J. Friction Wear* **30**, 118–126 (2009)
 - Cody, R.B., Laramée, J.A., Durst, H.D.: Versatile new ion source for the analysis of materials in open air under ambient conditions. *Anal. Chem.* **77**, 2297–2302 (2005)
 - Mazzotta, M.G., Pace, R.B., Wallgren, B.N., Morton III, S.M., Miller, K.M., Smith, D.L.: Direct analysis in real time mass spectrometry (DART-MS) of ionic liquids. *J. Am. Soc. Mass Spectrom.* **24**, 1616–1619 (2013)
 - Deguchi, S., Mukai, S., Sakaguchi, H., Nonomura, Y.: Non-engineered nanoparticles of C₆₀. *Sci. Rep.* **3**, 2094 (2013)