Electronic Supplementary Material (ESI) for Analyst.

Supporting Information

Real-time mass-spectrometric screening of droplet-scale electrochemical reactions

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Chemicals

Lithium triflate (96%), N,N-dimethylaniline (DMA, 99%), and acetonitrile (MS grade) were purchased from Sigma Aldrich (Darmstadt, Germany). Lithium triflate was first dissolved in acetonitrile to form a 0.1 mM lithium triflate solution. DMA stock solution was prepared by dissolving 3 μL of DMA into 1 mL lithium triflate solution, and was further diluted with lithium triflate solution to the desired working concentrations. The preparations, manipulations, and electrochemical analyses were carried out under atmospheric pressure and room temperature. All chemicals and reagents were used without further purification. All individual solutions were freshly prepared before use.

Electrochemical droplet cell setup

The electrochemistry controlling setup took inspiration from coupling of droplet spray ionization mass spectrometry (DSI-MS) with electrochemistry. In detail, the corner of the glass slip (1245-42A, Fischer Scientific, USA) was used as the reservoir for electrolyte as well as the spray ionization. A platinum-wire (0.5 mm) working electrode, coiled platinum counter electrode (0.5 mm), and an Ag/AgCl reference electrode completed the three-electrode system. These electrodes were employed as both for electrochemistry and charged droplet spray. When the potential was applied across the electrodes, the electrochemical reaction and the charged droplet spray were simultaneously triggered. The tip-to-cone distance was 3 mm. The working electrode-to-tip distance was 2 mm. Increasing this distance may result in a detection delay caused by diffusion of product. The angle formed between the MS inlet and tip-end was 3°−6°.

Power supply

Because the electrodes were employed both for electrochemical reaction and charged droplet spray, a custom-built power supply was used. There were two working modes: potentiostat mode and switch mode. In potentiostat mode, the potential across the electrodes was constant, while that for switch mode the potential was varied between 0 and a set voltage. The switch time was controlled by a waveform generator (Tektronix, Shanghai, China).

For the potentiostat mode, wire **1** was connected to the working electrode, and wire **2** was connected to the counter electrode. For the switch mode, wire **2** was connected to the counter electrode, and wire **3** was connected to the working electrode. Wire **4** was for the reference electrode. The potential between the electrodes was controlled by the “potential” knob, which could vary in a range of 0−10 V. The high voltage across the wires resulted from a DC power supply (HV-502P2, Lion Co., Tianjin, China). The amperemeter reflected the current in the electrolyte solution. The typical current is on the order of milliamperes and the typical resistance between the working electrode and the counter electrode is on the order of megaohms.

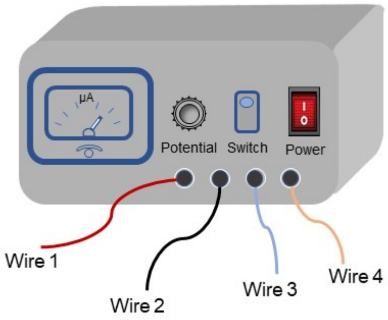

Fig. S1. Power supply for electrochemical reaction.

Instrument

All the experiments were carried out on an LTQ mass spectrometer (Thermo Fisher Scientific, Waltham, MA, USA). The mass spectrometer was operated in the positive ion mode. Full-scan mass spectra at mass-to-charge (*m/z*) of 50−500 were acquired and processed by the default Xcalibur package (Version 2.0.7, Thermo Fisher Scientific, US). Other parameters were set as follows: tube lens voltage, 110 V; capillary temperature, 275 C; and capillary voltage, 50 V. The collision-induced dissociation (CID) voltage was adjusted between 10 and 35 eV for best MS/MS results. Other parameters were set at default values.

Electrochemical reaction

The electrochemical reaction of DMA was performed as follows. Solutions of DMA were prepared in 0.1 mM lithium triflate at concentrations ranging from 0.024 mM to 2.4 mM. The operation workflow was as follow: (1) 20 μL of electrolyte solution was loaded onto the cover slip corner positioned in front of the MS inlet; and (2) a potential (E = 4.5 kV; ΔE = 2 V) was applied across the electrodes which simultaneously triggered the electrochemical reaction and the charged droplet spray. All experiments were carried out more than three times to make sure the data were reproducible.

Effect of high voltage on the electrodes

To evaluate the effect of high voltage on the electrochemical reaction, we compared the mass spectra obtained from conventional ESI with our approach. A DMA solution of 0.24 mM in 0.1 mM lithium triflate was used. The parameters for ESI-MS were as follows: high voltage, 4.5 kV; flow rate, 5 μL/min; and no nebulization gas. For coupling of DSI-MS with EC cell, the three electrodes held the same high voltage; thus, no potential existed across the electrodes (E = 4.5 kV; ΔE = 0 V). The mass spectra obtained from our approach compared well with the result of conventional ESI, indicating that the electrode setup had no influence on the electrochemical reaction.

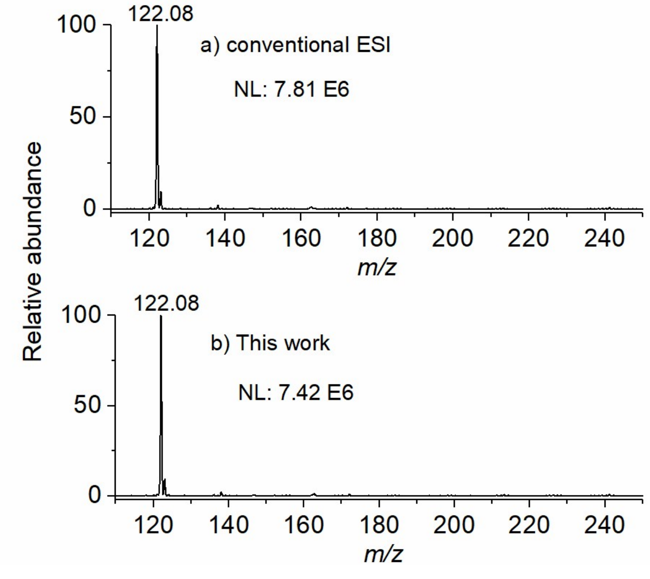

Fig. S2. Mass spectra obtained from (a) conventional ESI and (b) our approach.

Collision-induced dissociation of the DMA radical cation (*m/z* 121)

The electrolyte solution of 20 μL was loaded on the slip corner and an oxidizing potential of 2 V was applied across the electrodes (E = 4.5 kV; ΔE = 2 V). Because the signal intensity of *m/z* 121 was high enough for MS/MS experiment, no higher oxidizing potential was applied. The peak of *m/z* 121 was isolated with a 1.0 mass unit isolation width, and the normalized collision energy was 20 eV. The peak of *m/z* 120 was reported as a resonance stabilized aromatic imine[1].

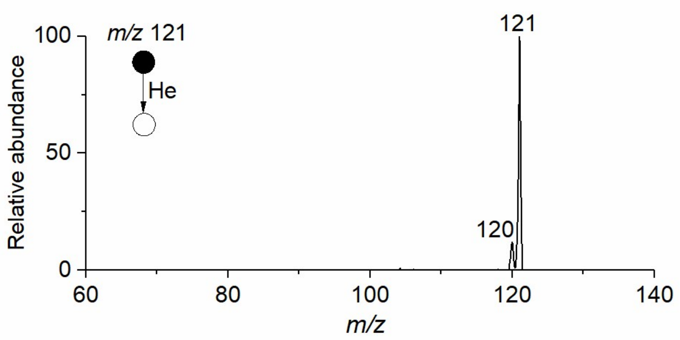

Fig. S3. MS/MS result of the DMA radical cation at *m/z* 121.

DMA electrooxidation with different electrode configurations

Two different electrode configurations were investigated. One electrode configuration used two platinum-wire electrodes with a diameter of 0.5 mm as the working electrode and counter electrode, respectively. Another electrode configuration used a coiled platinum wire (0.5 mm) as the working electrode while a piece of platinum with an area of 3.3 × 3.7 mm^2 was used as the counter electrode. The potential applied across the electrodes was 2 V (U = 4.5 kV; ΔE = 2 V). All the data were collected after applying potential across the electrodes.

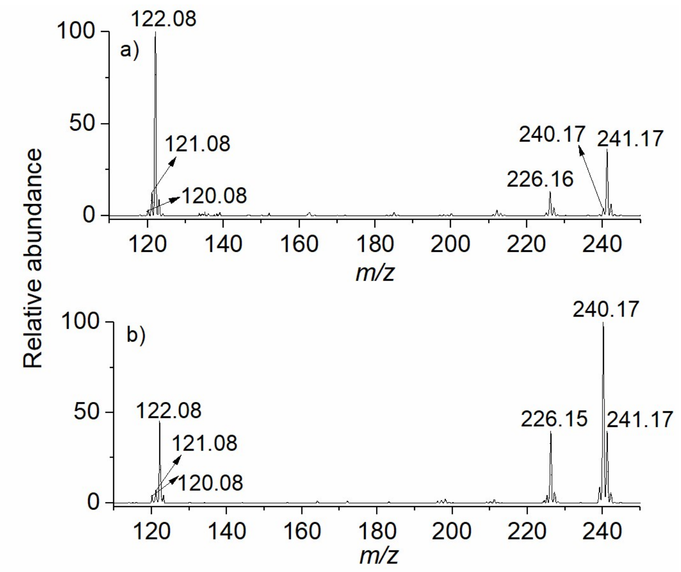

Fig. S4. Mass spectra of DMA electrooxidation with two different electrode configurations: (a) two platinum wires (one for working electrode, one for counter electrode); and (b) one coiled platinum wire (working electrode) and one piece of platinum sheet (counter electrode).

DMA electrooxidation at different concentrations

The electrochemical reaction of DMA was also investigated at different initial concentrations ranging from 0.024 to 2.4 mM, in order to evaluate the applicability of this method. The electrolyte solution loaded onto the corner was 20 μL. The applied potential across the electrodes was 2 V (*E*= 4.5 kV; Δ*E* = 2 V). The mass spectra were recorded after the potential was applied.

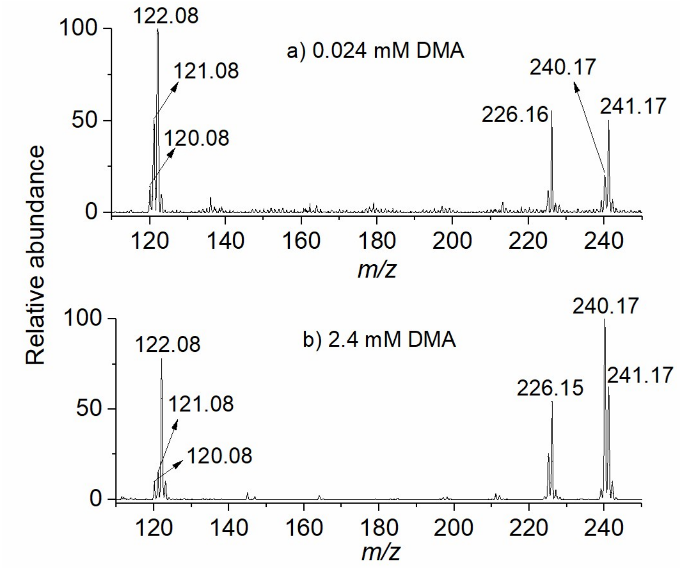

Fig. S5. Full positive-ion-mode mass spectra of the electrochemical reaction of DMA at a DMA concentration of (a) 0.024 mM and (b) 2.4 mM.

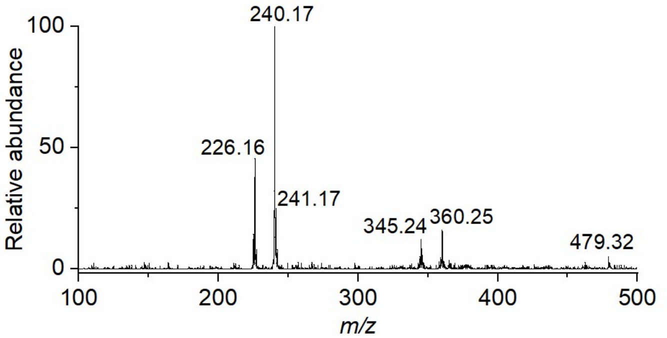

Fig. S6. Mass spectra of the electrochemical reaction of DMA (0.024 mM) at reaction time of 90 s.

Calculation of the half-life of the DMA radical cation

The dimerization of $DMA^{\bullet+}$ was reported to undergo a second-order kinetics with a measured rate constant of 2.5×10^8 $M^{-1}s^{-1}$[2]. Therefore, the half-life of DMA radical cation could be calculated using the equation[1]:

$$t_{1/2} = \frac{1}{k[DMA^{\bullet+}]_0}$$

where k is the second-order rate constant and $[DMA^{\bullet+}]_0$ is the initial concentration of $DMA^{\bullet+}$

In the present work, the signal intensities of TMB and $TMB^{\bullet+}$ were comparable or even higher than that of protonated DMA, thus indicating a significant conversion of DMA to $DMA^{\bullet+}$. We assumed that a full conversion of DMA to $DMA^{\bullet+}$ takes place in calculating the half-life of $DMA^{\bullet+}$, although complete conversion was impossible. In this regard, the initial concentration of $DMA^{\bullet+}$ was equal to that of DMA. Therefore, the half-life of $DMA^{\bullet+}$ was calculated, and listed in Table **S1**:

Table S1. Calculated half-life of DMA radical cation

Initial DMA concentration mM	Calculated half-life of $DMA^{\bullet+}$ μs
2.4	1.7
0.24	17
0.024	170

References

[1] T. A. Brown, H. Chen, R. N. Zare, *Angew. Chem. Int. Ed.* **2015**, *54*, 11183-11185.

[2] F. H. Cao, J. Kim, A. J. Bard, *J. Am. Chem. Soc.* **2014**, *136*, 18163-18169.