Development of a multi-turn time-of-flight mass spectrometer with an Atmospheric ionization

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Overview

- The API-MULTUM was developed. A dielectric barrier discharge ion source was used.
- The mass resolving power >10,000 was achieved.
- For more sensitive analysis and miniaturization, we are developing new API-MULTUM.

Introduction

In recent years, mass spectrometers which can operate on site and in real-time are required, because these instruments have widespread applications for example detection and identification of chemical and biological hazards for homeland security. To achieve on site real-time analysis, the mass spectrometer needs to satisfy the following specialty.

- small enough to carry
- high mass resolving power
- an atmospheric pressure ionization (API) source such as a direct analysis in real time (DART)

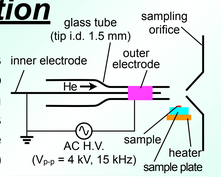
We have already developed a miniature multi-turn time-of-flight (TOF) mass spectrometer (MULTUM-S II) [1]. The size of a MULTUM-S II is 50.4 cm × 58.4 cm × 27.3 cm including vacuum system and high voltage circuit unit, and the resolution of it achieved 31600.

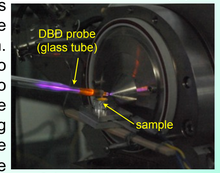
In this research, a dielectric barrier discharge(DBD) ion source was developed and an interface between API ion source and MULTUM-s was established.

Experimental

Ionization

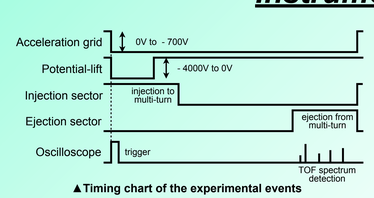
A DBD ion source was used as an API ion source[2,3]. To generated DBD plasma, AC high voltage ($V_{p\text{-}p}$=4 kV, 15 kHz) was applied to the outer electrode twisted around a glass (dielectric) tube and pure gaseous He gas was flowed in the glass tube. He gas flow rate was 100 ml/min. This flow rate was not enough to ignite DBD plasma but enough to maintain DBD plasma. Sample was located between the sampling orifice and the tip of glass tube and heated to 120 ℃ to facilitate vaporization.



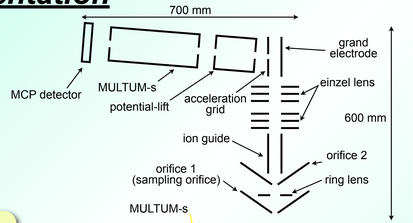


▲Schematic drawing and photograph of DBD ion source

Instrumentation

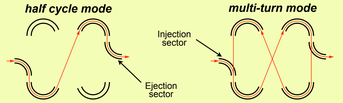


▲Timing chart of the experimental events



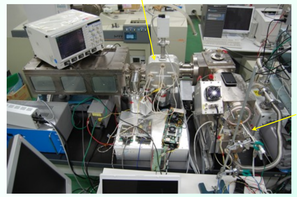
<MULTUM-s>

The MULTUM-s consisted an injection sector, an ejection sector and four homothetic sector electrodes. In general, TOF of a TOF mass spectrometer is proportional to the flight length. Therefore high resolution analysis is achieved by lengthening the flight path length with constant width of same *m/z* ion packet. The MULTUM-s fulfill this postulation by placed ions in a closed orbit and passed the ions around the same orbit (1 cycle = 625 mm) many times.



Ions pass the shortest path, so this mode is used for **sensitive analysis**.

Ions pass long path, so this mode is used for **high resolution analysis**.

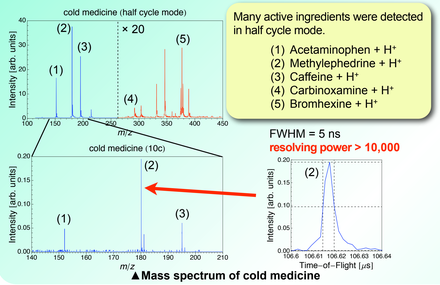


▲Schematic drawing and photograph of API-MULTUM

The API-MULTUM was developed based on the ESI-TOF/TOF[4]. The ion source consisted of an API ion source (ESI ion source for JMS-T100LC, JEOL, Akishima, Japan), two einzel lens and an OA block. The OA block was composed of a ground electrode, an acceleration grid and a potential-lift.

Pulsed voltage was applied to the acceleration grid, the potential-lift, the injection sector and the ejection sector. Continuous ion beam was supplied between the ground electrode and the acceleration grid, and then accelerated orthogonally by turning on the acceleration grid voltage (-700 V) and the potential-lift voltage (-4000 V). While ions were passing in the potential-lift, the potential-lift voltage were turned off. As a result, ions could go into grounded voltage field with accelerate energy. Ions accelerated in this way was injected into the MULTUM-s by the injection sector voltage. In half cycle mode analysis, injected ions pass the shortest path (0.5 cycle) and ejected. In multi-turn mode analysis, after ions injected, injection sector voltage was turned off to keep ions in the closed orbit. After a preset number of cycles, the voltage of the ejection sector was switched on and ions were ejected from the closed orbit.

Results & Discussion



Many active ingredients were detected in half cycle mode.

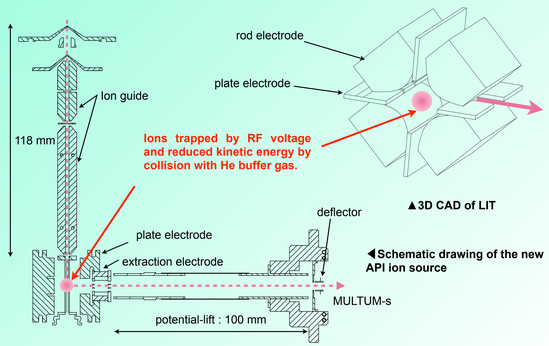
(1) Acetaminophen + H⁺
(2) Methylephedrine + H⁺
(3) Caffeine + H⁺
(4) Carbinoxamine + H⁺
(5) Bromhexine + H⁺

FWHM = 5 ns
resolving power > 10,000

▲Mass spectrum of cold medicine

Cold medicine was analyzed by the API-MULTUM. In half cycle mode, many active ingredients were detected. In multi-turn mode (10 cycles), resolving power of protonated methylephedrine was over 10,000. It is enough to discriminate objective molecule from uninteresting molecule. On the other hand, limit of detection (LOD) was roughly estimated tens ng. It is larger than reported in previous papers [2,3]. It is because width of the ion beam, which can orbit in MULTUM-s, was limited to less than 2 mm. Then in the analysis by developed equipment, small percent of ions supplied to the OA block were detected and most of them were lost.

Instrument under Development



▲3D CAD of LIT

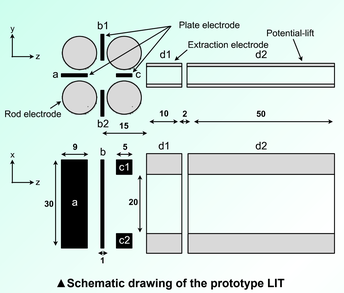
◀Schematic drawing of the new API ion source

The API-MULTUM achieved acceptable result as a prototype instrument, however it has two issues.

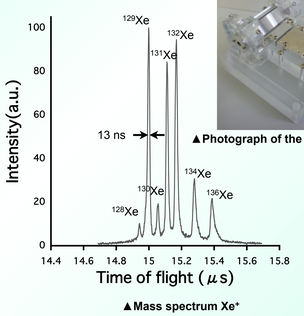
- The size of the instrument is not enough for on-site analysis (600×700×400 mm)
- The LOD is not small enough (approx. tens ng).

The first problem will be overcome by using smaller differential pumping system. The second problem will overcome by using the new linear ion trap (LIT). By the new LIT, the ions were once stored in the LIT and extracted orthogonally from the LIT forward to the MULTUM-s. The LIT consists of rod electrodes and plate electrodes. The shape of the rod electrodes are hyperbolic, and their radius of inscribed circle is 5.307 mm. The length of them was 28 mm. The plate electrodes, which are unique technique of this LIT, are inserted between the rod electrodes. Ions injected into the LIT were trapped and reduced kinetic energy by collision with He buffer gas. And then, the trapped ions are ejected from the gap between the rod electrodes by applying a pulsed voltage to the plate electrodes and extraction electrodes. Different from traditional OA, ions are once trapped and accelerated, so duty cycle will improve drastically.

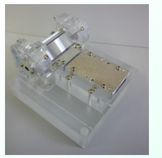
<preliminary research of new LIT>



▲Schematic drawing of the prototype LIT



▲Mass spectrum Xe^+



▲Photograph of the prototype LIT

To built the concept of new API-MULTUM, a prototype LIT was developed and evaluated. The radius of rod electrodes is 5.74 mm and their radius of inscribed circle is 5.00 mm. In this research ions were generated in the prototype LIT by electron ionization (a beam of 70 eV electrons had been passed through the LIT for 50 ms). Sample Xe gas was continuously leaked to the vacuum chamber. The pressure of the vacuum chamber was shifted from 9 × 10^{-5} Pa to 2 × 10^{-4} Pa by leaking Xe gas. Generated ions were trapped by RF voltage (1639 kHz, 200 $V_{0\text{-}p}$). After 150 ms trap, RF voltage was turned off and ions were extracted by applying plate electrodes voltage, HV of the extraction electrode and the potential-lift. The flight path length from the potential-lift to the MCP detector was approximately 800 mm. FWHM of ^{129}Xe was less than 13 ns. It mean this LIT achieved satisfactory time convergence.

Conclusion

The API-MULTUM with DBD ion source was developed. The resolving power was more than 10000. This meant smaller and more sensitive API-MULTUM will be useful on site real-time analysis.

Smaller and more sensitive API-MULTUM is developing now. It include orthogonal extraction LIT. Its size will be 500×300×400 mm, and LOD will be sub pg order.

Acknowledgment

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Reference

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[2] Harper J. D. et al. *Anal. Chem.* **2008**, *80*, 9097-9104
[3] L. C. Chen et al. *Rapid Commun. Mass Spectrom.* **2009**, *23*, 333-339
[4] Nagao H. et al. *J. Mass. Spectrom.* **2010**, *45*, 937-943