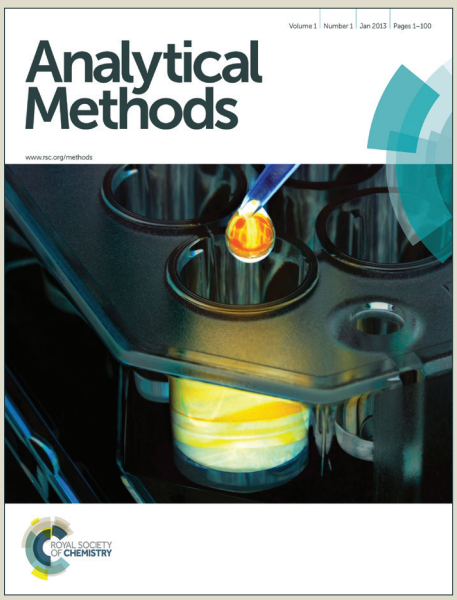
Analytical Methods

Accepted Manuscript



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Laser ionization/time-of-flight mass spectrometry for the direct analysis of emulsions

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Abstract

A direct method for the monitoring of emulsions was developed using laser ionization/time-of-flight mass spectrometry. A pair of concentric capillaries stably introduced an oil-in-water microemulsion into a mass spectrometer. The system was applied to the monitoring of a milky white emulsion. With this system, the average of the peak areas was calculated to monitor the local concentration of dispersed toluene, which was related to a collapse of the emulsion. Strong spikes appeared, particularly when the emulsion was measured during high turbidity, which suggested the existence of highly concentrated toluene in the emulsion. The mass of the constituents was measureable in both micro- and macroemulsions. Therefore, this method could be widely applied to emulsion studies that are needed for stability evaluation and quality control.

Introduction

Laser ionization/time-of-flight mass spectrometry (LI/TOFMS) has several advantages such as a superior optical selectivity and robustness against contamination.[1-5] Here, it was applied to the trace analysis and/or real-time monitoring of components in mixture samples.[6-11] This method is mainly used to measure gas samples. Solid or liquid samples normally are vaporized by heating or by laser ablation/desorption.[12-18] Though electrospray ionization (ESI)-MS is generally employed for the mass analysis of a liquid sample, LI/TOFMS may become a superior means for the detection of a liquid sample due to great advantages in spectroscopic selectivity. We recently reported the introduction of an aqueous solution directly into TOFMS to measure an aromatic compound.[19]

The target sample in the present study was an emulsion, which is a heterogeneous system wherein one liquid is dispersed as droplets into another liquid but is not dissolved, such as with oil and water. Emulsions exist in a diverse range of applications such as materials, foods, and pharmaceuticals.[20] Studies on the stability of emulsions are very important, because the condition of an emulsion can easily be changed, e.g., creaming, flocculation, coalescence, and Ostwald ripening.[20-22] The collapse process is quite complicated, and depends on several factors that includes the concentrations of the dispersoid and the surfactant. To date, several techniques have been used to evaluate emulsions: spectrometry, light scattering, and small X-ray scattering.[23-29]

To the best of our knowledge, an online mass spectrometric and stability evaluation approach of emulsions has not yet been accomplished. Normally, appropriate pretreatments such as drying or matrix addition are performed before the mass analysis.[30,31] Recently, the mass

spectra of surfactant-stabilized droplets have been reported using ESI.[32] If real-time monitoring of an intact emulsion in mass spectrometry could be achieved without pretreatment, the method would be quite useful for a detailed evaluation of the collapse process and for the quality control of an emulsion. Further applications of the method also would be possible. Study on the kinetics of emulsion polymerization would be one example.[33]

The use of LI/TOFMS for the real-time monitoring of an emulsion was first developed in the present study. Using an oil-in-water (O/W) emulsion, a stable sample introduction method was investigated, and the application of this method for the measurement of an unstable milky emulsion is discussed here.

Experimental

Reagents and sample preparation

Toluene, sodium dodecyl sulfate (SDS), and 1-pentanol were all purchased from Wako Pure Chemical Industries (Osaka, Japan) and used as a dispersoid, a surfactant, and a co-surfactant, respectively. In the sample preparation, SDS and 1-pentanol were added to distilled water, and it was shaken manually. Then toluene was slowly added, and the mixture was shaken manually and/or sonicated. The mixture was sealed and left at room temperature for at least a few days until use. The final concentrations are mentioned in each figure caption. In the present study, two types of emulsions, a transparent microemulsion and a milky emulsion (macroemulsion), were prepared. The transparent microemulsion remained clear for an extended period of time,

but a collapse phenomenon, likely to be creaming, was observed in the case of the milky emulsion.

Apparatus

The LI/TOFMS instrument used in the present study is shown in Figure 1, as described in the literature.[19,34]

Two types of the sample introduction technique were examined in the present study. In the first, an emulsion was introduced using a single deactivated fused-silica capillary (GL Sciences), and the second used a pair of concentric capillaries, as illustrated in Figure 1. In the latter case, the emulsion was passed through the inner capillary (outer diameter; 150 μm), while ambient air or nitrogen gas was introduced from the outer column. The flow rate of the gas was ca. 2 mL/min in the present study; in some cases, that was adjusted by a flow meter (Kofloc, RK-1250, Kyoto, Japan). The pressure in the chamber was ca. 2×10^{-3} Pa when using a single capillary and ca. 1×10^{-2} Pa or below when using a pair of concentric capillaries. The length of the capillary column for the passage of the emulsion was ca. 450 mm. The position of the tip of the inner column was set 2-3 mm inward from that of the outer column. The inlet side of the capillary was directly inserted into a sample container with rims that were sealed with a piece of parafilm, while a lid with a small hole for passage through the capillary was used in the experiment shown in Figure 5 in order to suppress the sample volatilization. The inlet side of the capillary was set a few centimeters from the bottom of the container. The capillary column was set almost even with the ground.

The fourth harmonic emission of a Nd:YAG laser (Rayture Systems, GAIA II, 10 Hz, 266 nm, 20-400 μJ, 4 ns, Tokyo) was used for ionization. The laser was focused with a plano-convex lens with a focal length of 200 mm. The ionization position was adjusted to 2 mm from the capillary tip. A linear-type TOFMS, which is now commercially available (Hikari-GK, HGK-1, drift length 60 cm, Fukuoka, Japan), was used in the present study. The capillary nozzle was indirectly heated by raising the temperature of the flange to 40 ^{o}C. The ion signals were detected by a microchannel plate assembly (Hamamatsu Photonics, F4655-11, Shizuoka, Japan) and were recorded using either a digitizer (Acqiris/Agilent Technologies, AP240) or a digital oscilloscope (Tektronix, TDS5104). All data were recorded after a certain time following the insertion of the capillary into the sample. In the present study, the ionization laser was introduced 10-30 seconds after starting the recording in order to determine the baseline level. In the measurement of Figures 2 and 3, the data were recorded without averaging, i.e., the signal intensity was acquired every 0.1 seconds. On the other hand, an average of 5 laser shots was applied in the experiment shown in Figure 5 in order to reduce the data volume arising from an extended period of recording. The data were processed and analyzed with a program constructed in-house using LabVIEW programming software (National Instruments).

Results and discussion

Introduction of a microemulsion using a single capillary

The sample introduction was first applied using a single capillary column. Figure 2 shows a two-dimensional display of the data for a microemulsion using a capillary with an inner diameter

of 50 μm. In this figure, two lines arising from a toluene ion (m/z = 92) and a fragment ion (m/z = 91, a tropylium ion was one of the candidates) were primarily observed. It seemed odd that these lines seemed to be in waves, or in other words, that the flight times were frequently shortened. The result of the selected ion monitoring of the corresponding species, which was constructed by extracting the region of ca. 10 μs with regards to flight time, is also shown in Figure 2. Several spikes, which had simultaneously arisen when the flight times were shortened, can be observed in the figure. These results can be explained by assuming that the initial velocity and the concentration of toluene molecules both were often increased at the ionization point, probably due to the explosive introduction of an emulsion that had accumulated at the tip of the capillary. A fluctuation in the flight time is inappropriate for calculating the mass of an analyte, and, therefore, the introduction method using a single capillary was considered to be unsuitable for emulsion analysis.

Introduction of a microemulsion using a pair of concentric capillaries

In order to correct the flight time fluctuation, as shown in Figure 2, several experimental conditions were modified. First, a pair of concentric capillaries, rather than a single capillary, was employed as a sample introduction technique. The result is shown in Figure S1 (Supplemental information), where the inner diameter of the inner capillary was 50 μm. In this case, though spikes still appeared, the fluctuation of the flight time almost disappeared. These results suggest that, despite the fact that the explosive sample introduction still existed, the initial velocity of the analyte molecules became constant by introducing the gas from the outer capillary.

In order to suppress the explosive introduction, an inner capillary with a smaller inner diameter was employed to reduce the amount of the analyte molecule per unit of time. Schepler et al. have reported that they employed a thinner capillary (inner diameter; 25 μm) to prevent the formation of droplets at the tip, although their configuration for liquid sample introduction was considerably different from that of the present study.[35] Figure 3 shows an example of the result using an inner capillary with an inner diameter of 20 μm. Neither the spikes nor the fluctuation of the flight time was observed. As a result, the modification of the capillary configuration for applying the outer gas and the use of an inner capillary with a smaller inner diameter reduced the size of the species undergoing laser ionization from small droplets to clusters to possibly even isolated molecules. Note that, though the deviation of the signal intensity of the selected ion monitoring seems large at first glance, the figure is depicted using raw data, and of course it can be altered with effects such as smoothing in order to reduce the deviation when requested. The mass spectrum obtained using this experimental condition is shown in Figure 4. A selective measurement was definitely achieved, i.e., only the peaks of toluene and the fragment were observed, while the peaks of SDS (m/z = 288) or 1-pentanol (m/z = 88), the concentrations of which were about 1 order of magnitude higher than that of toluene, were not detected.

The appropriate experimental conditions to stably introduce an emulsion are as follows: (1) a smaller inner diameter of the inner capillary is preferable, e.g., 20 μm is preferred and 50 μm is too large; (2) the position of the tip of the inner capillary should be set 2-3 mm inward from the tip of the outer diameter, and when the tips of both capillaries are true, the spikes are substantially observed. There was an additional problem with this sample introduction method. Once the inner capillary was removed from the bottle containing the emulsion and attempts were made to measure the next sample, the flow of the emulsion was often stopped due to the clogging

of SDS. The cause of this problem remains unknown, but the capillary can easily be exchanged with a new one if it occurs.

Monitoring of a milky emulsion

The present method was applied to the measurement of a milky white emulsion. Figure 5 shows the time course of the peak area for a milky emulsion (black line), and that of the peak area averaged every 30 seconds is also shown (red line) in order to simply judge the obtained results. For this measurement, the emulsion container was handled gently. After that, the capillary was inserted into the lower part of the container and left for at least 30 minutes, and then the container was shaken by hand to give the emulsion a white turbidity. As shown in this figure, the red line indicates that the average peak area was increased a few minutes after shaking, and then decreased with elapsed time. The time course of the peak area was considered to be the concentration of toluene at the sampling point, and the decay was correlated to the collapse of an emulsion such as creaming. The peak area approached a nearly constant value, which meant that a certain concentration of toluene was present, e.g., as a microemulsion, after the visible creaming.

It is noteworthy that many strong spikes appeared by the peak area depicted with a black line after the emulsion had gained turbidity, then subsequently, the number, as well as the height, of the spikes gradually decreased. It is true that the average signal area showed the same tendency, but this does not mean that both forms of data provide the same information about the local environment in an emulsion. That is to say, that although the possibility of an unstable sample introduction cannot be denied, as discussed previously, it is reasonable to assume that the

arising spikes were caused by the introduction of highly concentrated toluene, e.g., toluene droplets, into the inlet of the capillary, and/or the occurrence of a collapse, such as flocculation, during passage through the capillary column. The decrease in the spikes could be explained by a decrease in the domain of highly concentrated toluene around the inlet. Good reproducibility of the appearance of strong spikes could have been obtained by measuring the emulsions with high turbidity.

In the present study, the real-time monitoring of emulsions, even where the local concentrations and conditions were dramatically changed, was achieved using LI/TOFMS. The average peak area, as well as the spikes, can provide interesting information about the stability of an emulsion. The tendencies towards decreases that were demonstrated were considered to be a function of the sampling point; they may be increased in other sampling points. Other methods for evaluating the stability of an emulsion should be used and compared against the results obtained in the present study. Fortunately, the present system can easily be combined with several other conventional methods,[26,27] since the capillary was simply inserted into the container of an emulsion with no other interference.

Conclusions

An on-line mass analytical method of emulsion was developed using LI/TOFMS. The local concentration of dispersed toluene in both the micro- and macroemulsions was measurable by the average peak area. In addition, the existence of high concentrations of toluene, such as droplets, was observable by the characteristic spikes. All the results could be obtained with no pretreatment as demonstrated. From the point of view of the advantages such as selectivity and

robustness, LI/TOFMS can be suitable for the evaluation of an emulsion with inherently high concentrations of each component. Therefore, this method could be a powerful tool to evaluate the stability of emulsions and could be useful for many applications, such as the quality control of emulsions and the monitoring of intermediates/products generated from emulsion polymerization.

Acknowledgments

This research was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS). This work was also supported by a research grant provided by The Iwatani Naoji Foundation.

Supplemental information

Supplementary data associated with this article are available on the Web of *Analytical Methods*.

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Figure Captions

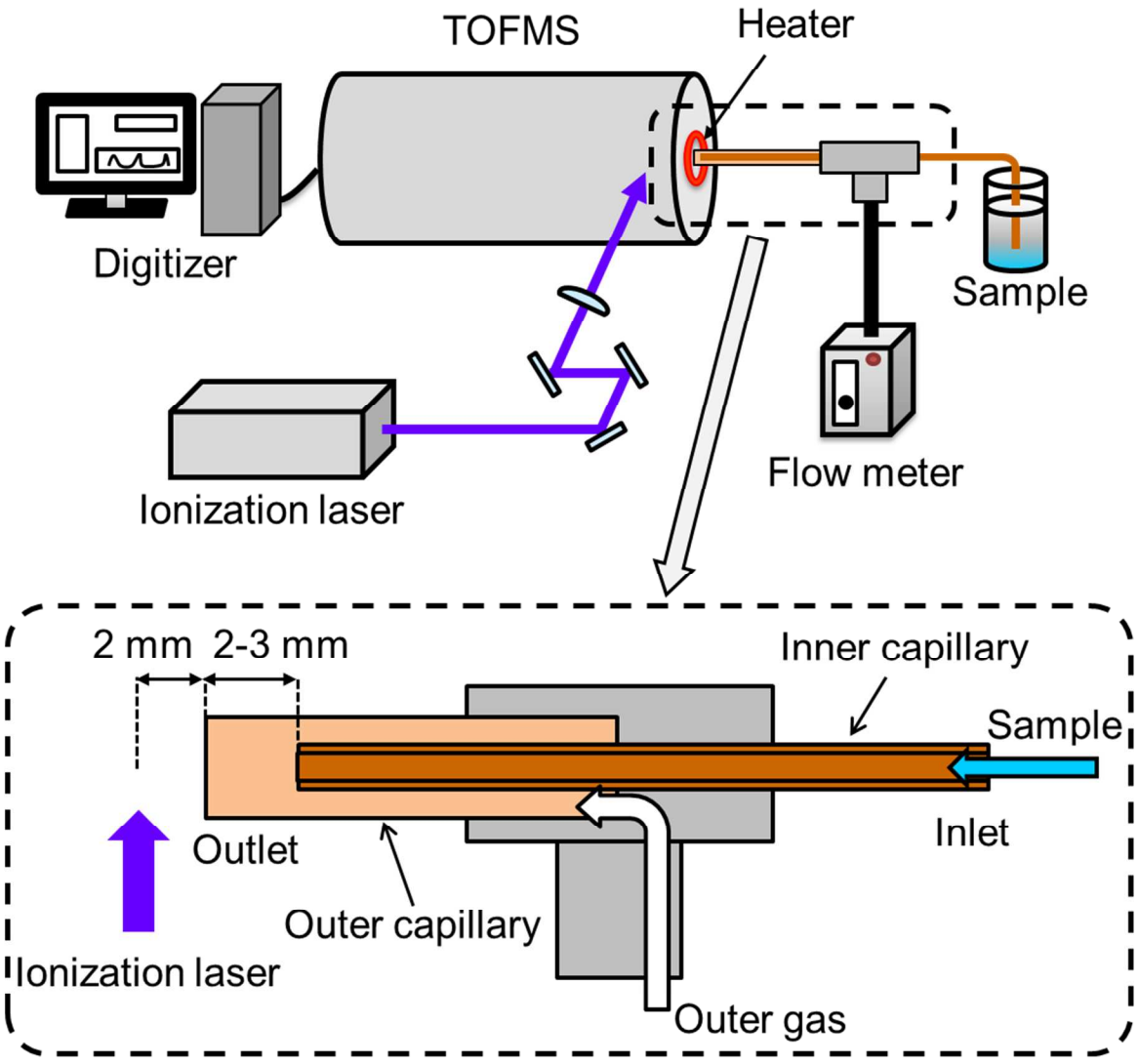
Figure 1. Experimental apparatus of LI/TOFMS. An enlarged view of a pair of concentric capillaries for sample introduction is also shown.

Figure 2. Two-dimensional display for a microemulsion obtained using a single capillary for sample introduction. The inner diameter of the capillary was 50 μm. The time course of the peak area of observed ions, as indicated in the display, is also shown. Concentration: 500 ng/μL for toluene, 10,200 ng/μL for SDS, and 6,300 ng/μL for 1-pentanol.

Figure 3. Two-dimensional display for a microemulsion obtained using a pair of concentric capillaries where the inner diameters of the inner and outer capillaries were 20 and 250 μm, respectively. The time course of the peak area of toluene ion is also shown. Concentration: 400 ng/μL for toluene, 6,600 ng/μL for SDS, and 3,000 ng/μL for 1-pentanol.

Figure 4. Mass spectrum for a microemulsion averaged from 200 single transients. The experimental conditions were the same as those in Figure 3.

Figure 5. Time course of the peak area of toluene in an unstable emulsion (black line). The red circle/line exhibits the results of the black line averaged every 30 seconds. The photos of an emulsion taken at different times are indicated by gray arrows. The inner diameters of the inner and outer capillaries were 25 and 320 μm, respectively. Concentration: 5,000 ng/μL for toluene, 5,700 ng/μL for SDS, and 3,000 ng/μL for 1-pentanol.



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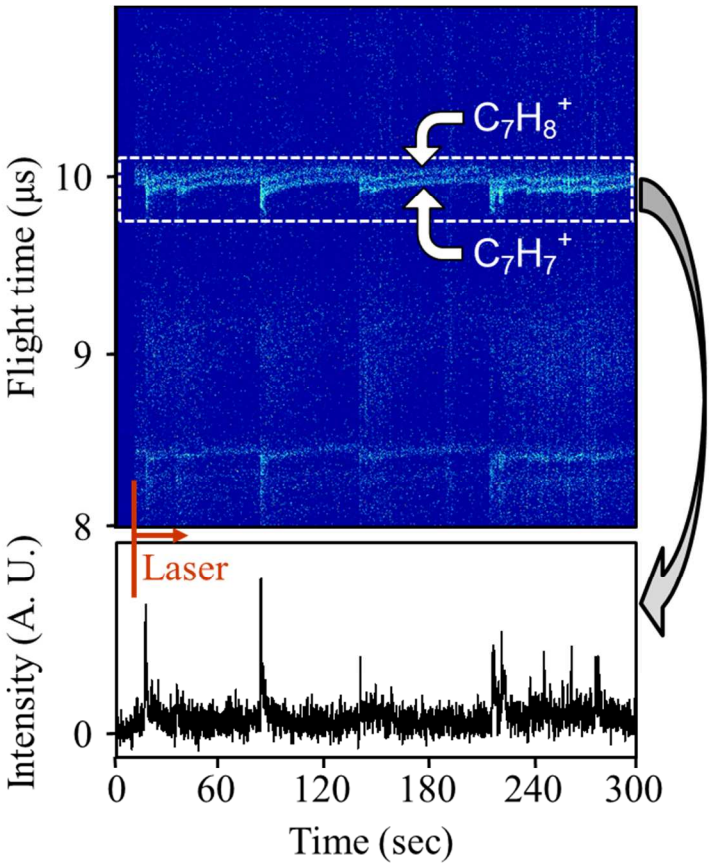

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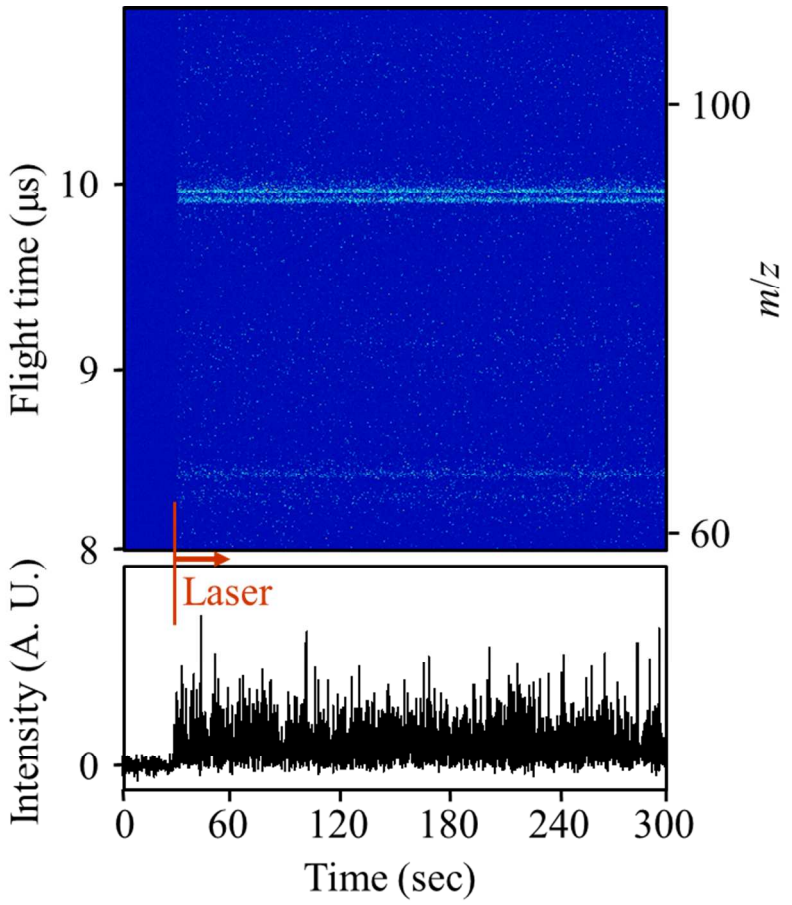

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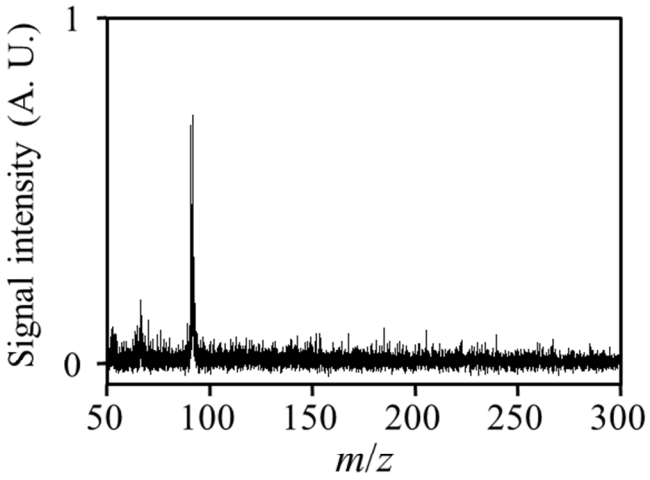

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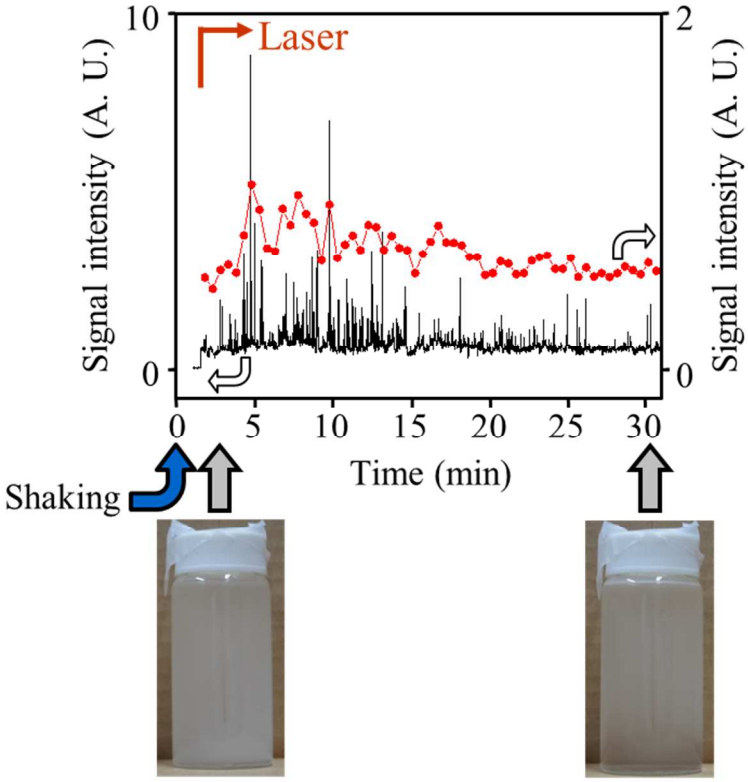

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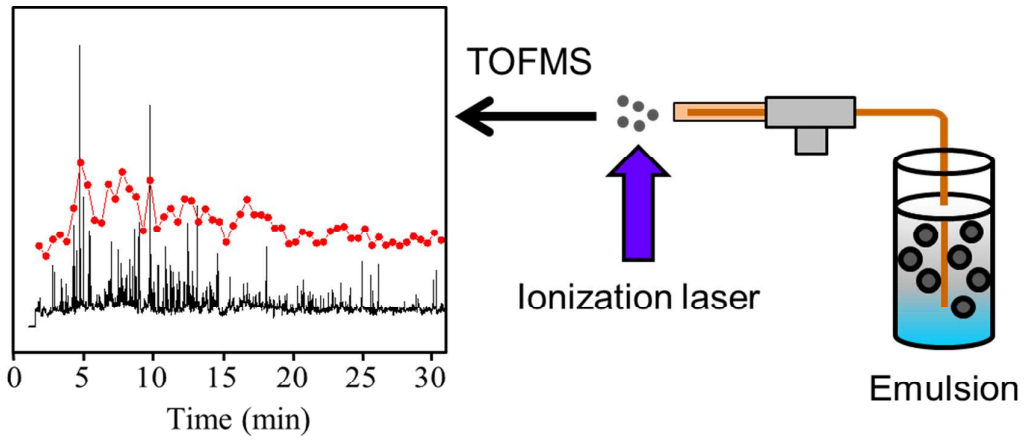

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