

Detection of Mass 31 830 Ions with an External Ion Source Fourier Transform Mass Spectrometer

Sir: The analysis of high mass ions by Fourier transform mass spectrometry (FTMS) has been demonstrated in several laboratories (1-5). The highest m/z reported thus far is the cesium iodide cluster $[\text{Cs}(\text{CsI})_{62}]^+$ at 16 241 daltons (2). The spectrometer used for these experiments had a 3-T magnet and a single section trapped ion analyzer cell. Ions were produced by bombarding a cesium iodide sample with a beam of 10-keV cesium ions. Other experiments (3) performed with a 7-T magnet and a dual trapped ion analyzer cell have demonstrated that laser desorption FTMS can provide high resolution mass spectra for potassium-attached oligomer ions of poly(ethylene glycol)-8000. A mass resolution of 60 000 was achieved for m/z 5922, and identifiable peaks were obtained up to m/z 9700.

In both of the studies just cited, a direct insertion probe was used to position the sample inside the magnetic field, adjacent to one of the trapping plates of the analyzer cell. Ions produced by a laser pulse or cesium ion bombardment were trapped and detected in the analyzer cell. This method of introducing samples works well in some cases, but the range of applications is limited because volatile components or impurities in the sample increase the pressure in the FTMS analyzer cell and cause a loss of resolution and sensitivity.

Recently, a number of laboratories have begun to work on an alternative approach that is far more flexible: the ion source is placed outside of the magnetic field and is separated from the FTMS analyzer cell by several stages of differential pumping (4-14). The first experiments of this type were reported by McIver and co-workers in 1983 (6). The ion source of their instrument was a conventional quadrupole mass spectrometer that was outside of the magnet, about a meter from the analyzer cell. A novel feature of the instrument was a second long radio frequency (rf) quadrupole lens that focused the ions and guided them through the fringing fields of the magnet. Without the focusing provided by this lens, ions were not transmitted efficiently to the FTMS analyzer cell because of the magnetic mirror effect (7, 8). The first experiments were done with an electron ionization source. Subsequent experiments, done in collaboration with D. F. Hunt and J. Shabanowitz at the University of Virginia, demonstrated that the method could be used for fast atom bombardment (FAB) ionization of small peptides (9, 10). Further improvements made by Hunt and co-workers resulted in the first FAB-FTMS mass spectra of porcine insulin at m/z 5777 and horse cytochrome *c* at m/z 12384 (4). External ion source FTMS experiments have also been performed by using electrostatic lenses, rather than a rf quadrupole lens, to inject the ions (11-14).

Recently, we completed the construction of a new external ion source FTMS instrument that uses a single, long rf quadrupole lens to inject the ions (5). This instrument is less complicated than the original external ion source design because only two controls (quadrupole rf voltage level and frequency) are needed to select the range of injected ions. Initial results with the new instrument showed very good sensitivity and a mass resolution of 53 000 at m/z 9746. By use of impulse excitation instead of rf chirp excitation, the upper mass limit of the instrument was extended to 13 000 daltons (15-17).

In the present study, we report on the factors that influence the upper mass limit and the range of masses that can be analyzed with the new instrument. With conventional quadrupole mass spectrometers both rf and dc voltages are applied to the rods. This produces a narrow-band mass filter that passes only one m/z value at a time. In contrast, the

rf-only operating mode produces a band-pass mass filter that transmits a broad range of masses between certain high mass and low mass cut-offs. To determine these cut-off points, mass spectra of cesium iodide cluster ions have been acquired under various operating conditions.

EXPERIMENTAL SECTION

A schematic drawing and description of the new external ion source FTMS instrument has been published previously (5). Briefly, there are three differentially pumped regions that contain an ion source, a rf quadrupole lens, and a FTMS analyzer cell. Pumping restrictions between the regions produce a pressure gradient as large as 4000:1 between the ion source and the analyzer cell. The analyzer cell is centered in the homogeneous region of a horizontal bore, 6-T superconducting magnet manufactured by Oxford Instruments. Control pulses for the ion source, rf quadrupole lens, and FTMS analyzer cell were generated by an OMEGA data system manufactured by IonSpec Corp.

In a typical experiment, a thin layer of cesium iodide is coated on a copper probe tip and inserted into the source region through a vacuum lock. The sample is ionized by a 100-ms pulse from a 10-keV cesium ion gun, and at the same time a 1000-V, 1-MHz sine wave signal is applied to the quadrupole rods. The coherent cyclotron image current signal produced by the ions in the analyzer cell is digitized at a rate of 200 kHz by using a 12-bit analog-to-digital converter. The FFT calculations are done with two zero fills to increase the number of data points across each peak and improve the mass measurement accuracy.

RESULTS AND DISCUSSION

The performance of the new instrument is demonstrated by the mass spectrum in Figure 1 of cesium iodide cluster ions from m/z 1000 to 32 000. The peaks are labeled by the cluster size number n , according to the general formula $[\text{Cs}(\text{CsI})_n]^+$. The range from m/z 20 000 to 32 000 is shown expanded $\times 20$ so that the low abundance, high mass peaks can be seen. Figure 2, which is an expanded section from the same mass spectrum, shows the results for the $n = 62$ cesium iodide cluster ion at m/z 16 241. This peak, which was the previous upper mass limit for FTMS, is easily detected by our instrument with quite good signal-to-noise ratio and resolution. The full width at half height is 37 u, giving a mass resolution of $M/\Delta M = 439$. Previously we reported that the narrow-band acquisition mode could be used to get a high-resolution spectrum for the peak at m/z 9746, but this method did not seem to work for the much lower abundance peak at 16 241. The reason for this is not understood at this time.

Figure 1 shows that the present instrument configuration has an upper mass limit of m/z 31 830, which corresponds to the cluster $[\text{Cs}(\text{CsI})_{122}]^+$. Strong peaks for other high mass ions at $n = 82, 87, 97, 102,$ and 112 are also apparent. Table I compares the measured m/z values for these and other peaks with the exact masses for the various clusters. Even for the high mass ions, the agreement is very good. The measured m/z values are calculated from the measured cyclotron frequencies by using a single calibration equation of the form

$$m = \frac{A}{f} + \frac{B}{f^2} + \frac{C}{f^3} \quad (1)$$

This equation is applied across the full mass spectrum. The calibration constants A , B , and C are determined by a least-squares fit between the measured cyclotron resonance frequencies, f_i , and the exact masses, m_i , for 11 peaks in the spectrum. The last column in Table I shows that above m/z 20 000 the mass measurement error is a just a few mass units,

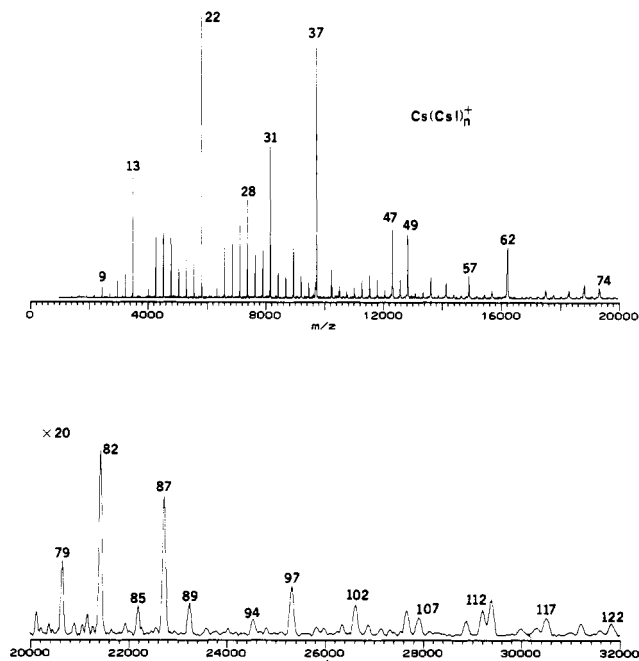


Figure 1. Mass spectrum of cesium iodide cluster ions obtained with an external ion source Fourier transform mass spectrometer. The peaks are labeled by the number of CsI units in the cluster, according to the general formula $[\text{Cs}(\text{CsI})_n]^+$.

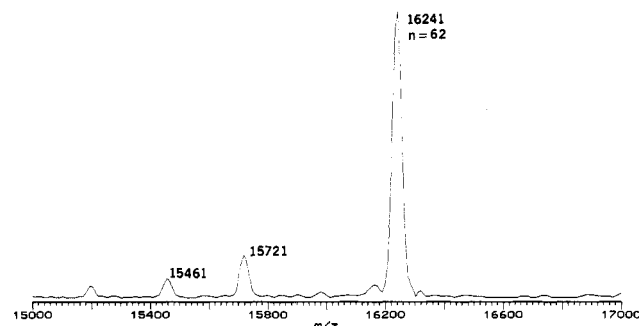


Figure 2. Improved mass resolution and sensitivity achieved for the peak at m/z 16241, which was the previous upper mass limit for FTMS.

even though the peaks in this range are about 80 u wide. Ijames and Wilkins have shown that even higher mass measurement accuracy (8.59 ppm between m/z 5500 and m/z 6000) can be achieved with FTMS by using ion ejection and narrow-band detection (3).

Previous experiments have shown that the transmission efficiency of the rf quadrupole lens depends on the voltage and frequency of the signal that is applied to the rods (5). With a rf voltage of 300 V, the upper mass limit is about m/z 6000, and with 600 V, the upper mass limit is about m/z 13000. The present results show that even higher rf voltage (1000 V) is needed to inject ions in the range 20000 to 30000 u. This effect is qualitatively similar to the results of Yost et al. for operation of the rf-only quadrupole that is used as a collision chamber in a triple quadrupole mass spectrometer (18). They calculated that the upper mass limit increases as $V^{5/2}$, where V is the rf voltage applied to the quadrupole rods. With the external ion source FTMS instrument, such a strong dependence on V is not observed, and it is likely that the fringing fields of the magnet interact with the quadrupole rf electric field to alter the trajectories of the ions.

Another feature of the quadrupole injection method is that the lower mass cut-off also increases as the rf voltage is increased. For example, in Figure 1 the abundant cesium iodide clusters below m/z 2000 are not seen in the spectrum because

Table I. Comparison of Measured Masses and Exact Masses for Cesium Iodide Cluster Ions: $[\text{Cs}(\text{CsI})_n]^+$

cluster size, n	measured m/z	exact mass	error
5	1431.97	1431.95	0.02
9	2471.20	2471.19	0.01
13	3510.33	3510.43	-0.10
22	5848.37	5848.71	-0.34
31	8186.83	8187.00	-0.17
37	9745.66	9745.86	-0.20
47	12343.99	12343.95	0.04
49	12864.13	12863.57	0.56
57	14939.98	14942.05	-2.07
62	16240.98	16241.09	-0.11
74	19360.33	19358.81	1.52
79	20655.84	20657.86	-2.02
82	21435.78	21437.28	-1.50
87	22734.50	22736.33	-1.83
89	23255.19	23255.95	-0.76
97	25336.12	25334.43	1.69
102	26633.71	26633.48	0.23
112	29229.04	29231.57	-2.53
117	30521.04	30530.62	-9.58
122	31831.96	31829.67	2.29

they are not transmitted by the quadrupole when a 1000-V, 1-MHz signal is used. This feature is useful for experiments that utilize a fast atom bombardment source because the intense low mass peaks that come from the liquid matrix are prevented from reaching the FTMS analyzer cell. To inject low mass ions, it is necessary to use lower voltages and/or higher frequencies for the rf quadrupole, but then the upper mass limit is also decreased.

Previous experiments on cesium iodide cluster ions using magnetic sector (19–21), time-of-flight (22, 23), and Wein filter (24, 25) mass spectrometers have shown that the ion currents and relative abundances of the high mass clusters are very low. One of the conclusions of the present study, therefore, is that the FTMS image current detection method has adequate sensitivity for the detection of low abundance, high mass ions up to m/z 30000. Another conclusion is that the rf quadrupole lens functions like a filter so that a broad range of masses between certain low mass and high mass limits are transmitted to the FTMS analyzer cell. Preliminary experiments have shown that adding a small differential dc voltage to the quadrupole rods causes a narrower range of ions to be injected, just as expected. However, this also causes the injection efficiency to decrease substantially. Now that these general features of the quadrupole injection method have been identified, we plan to develop a quantitative model of the magnetic and electric fields so that ion trajectory calculations can be performed to optimize the design and performance of the instrument.

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¹ Current address: IonSpec Corporation, 17951 Skypark Circle, Suite K, Irvine, CA 92714.

Carlito B. Lebrilla
Diana T.-S. Wang
Richard L. Hunter¹
Robert T. McIver, Jr.*

Department of Chemistry
University of California
Irvine, California 92717

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