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FUNDAMENTAL ASPECTS AND APPLICATIONS OF FOURIER-TRANSFORM ION-CYCLOTRON RESONANCE SPECTROMETRY

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SUMMARY

The operating principles, features, advantages, applications and potential of Fourier-transform ion-cyclotron resonance (F.t./i.c.r. or F.t.m.s.) mass spectrometry are discussed. It is shown that F.t./i.c.r. technology creates a high-performance mass spectrometer with high speed, high sensitivity, ultrahigh mass resolution, very wide mass range and unparalleled versatility.

The subject matter of this paper is derived from an earlier form of a particular type of mass spectrometry called ion-cyclotron resonance (i.c.r.) mass spectrometry [1, 2]. The application, a decade ago, of Fourier multiplex concepts [3, 4] to i.c.r. mass spectrometry created a new technique called Fourier-transform ion-cyclotron resonance mass spectrometry (F.t./i.c.r.) [5—7]. The term Fourier-transform mass spectrometry (F.t.m.s.) is also in common use today as an exact synonym for F.t./i.c.r. and this new technique.

There is potentially some confusion in using the term F.t.m.s., as Fourier techniques have also been applied with advantage to another type of mass spectrometer called a time-of-flight (t.o.f.) mass spectrometer [8]. It should be noted that in this paper and the other papers in this issue, "Fourier-transform mass spectrometry" and "F.t.m.s." are synonymous with F.t./i.c.r. and do not refer to Fourier-transform time-of-flight (F.t./t.o.f.) mass spectrometers.

PRINCIPLES OF ION-CYCLOTRON RESONANCE

The physics of ion-cyclotron resonance is very simple and follows from the elementary principles of electromagnetism [9]. In a uniform magnetic field, B, a moving ion of charge, q, and mass, m, will be subjected to a force called the Lorentz force, which acts perpendicular to the direction of ion motion. Solution of the equation of motion for the ion shows that the ion will be constrained to a circular orbit, with radius proportional to the velocity of the ion. The ion will have a characteristic frequency, ω, called the cyclotron frequency, for its orbital motion:

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$$\omega = qB/m \tag{1}$$

For a magnetic field of 1 Tesla and a mass range of m/q = 15—1500 Daltons, the cyclotron frequencies lie between 10 kHz and 1 MHz, and are thus in the radiofrequency band of the electromagnetic spectrum.

The equation $\omega = qB/m$ is called the cyclotron equation. It follows from this equation that an ensemble of ions of differing masses will be characterized by a spectrum of cyclotron frequencies. Measurement of the cyclotron frequencies of an ensemble of ions is thus, via Eqn. 1, tantamount to measuring the masses of the ions. Any instrument which measures the masses of ions is called a mass spectrometer and Eqn. 1 provides the fundamental relationship for the operation of an i.c.r. mass spectrometer.

The measurement of cyclotron frequencies is accomplished with two operations: excitation of cyclotron motion and detection of excited cyclotron motion.

Excitation of cyclotron motion

Figure 1 shows a schematic diagram of the equipment required for i.c.r. excitation. A parallel-plate capacitor is connected to a radiofrequency oscillator which creates an alternating electric field within the capacitor. If the frequency of the alternating electric field equals the natural cyclotron frequency for a particular ion (Eqn. 1), energy will be transferred from the radiofrequency oscillator to the kinetic energy of the ion. Because the kinetic energy is related to cyclotron radius, r, by

$$\mathrm{KE} = 1/2\, m\, \omega^2\, r^2 \tag{2}$$

the radius of the ion orbit will increase. The phenomenon of transferring energy in the manner just described is called "ion cyclotron resonance" or "i.c.r. excitation". It can be used to accelerate the ion, or any charged particle for that matter, to very high translational energies [10]. When cyclotron resonance is used for accelerating particles to very high energies, the apparatus is called a cyclotron [10]. When cyclotron resonance is used to measure ion masses, the apparatus is called an ion-cyclotron resonance mass spectrometer [1, 2].

Detection of excited cyclotron motion

Prior to i.c.r. excitation, all ions are moving with random phase relative to each other. During i.c.r. excitation all ions of a given mass are accelerated together and the instantaneous average position of the ions, called a rotating electric monopole [11], moves on the spiral path shown in Fig. 1. The rotating monopole induces a charge on the plates of the capacitor [11]. When the plates of the capacitor are connected by an external circuit an alternating current, called the i.c.r. signal current, will be created in this circuit by the rotating electric monopole [11] (Fig. 2). The frequency of the signal current is the cyclotron frequency. In F.t./i.c.r. practice, the current is converted to a voltage and the i.c.r. signal voltage becomes [11]

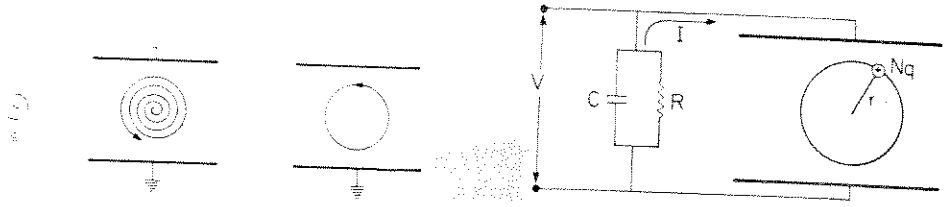

Fig. 1. Ion-cyclotron resonance excitation. An alternating electric field is created inside a capacitor and excites the cyclotron motion of an ion in the capacitor. The ion follows a spiral path as its motion is excited. After the oscillator has been turned off, the ion follows the path on the right. The coherent motion on the right is the rotating electric monopole which generates the i.c.r. signal (Fig. 2). For a magnetic field directed into the plane of the figure, a positive ion will follow the counterclockwise paths shown.

Fig. 2. Ion-cyclotron resonance detection. The rotating electric monopole induces an alternating charge in the plates of the capacitor and an alternating current, I, in the external circuit. The voltage, V, across this circuit (Eqn. 3) is the i.c.r. signal voltage.

$$V(t) = N\,q\,r/(d\,C)\cos\omega t \qquad (3)$$

where N is the number of ions, C is the circuit capacitance and d is the capacitor spacing. It should be noted that the i.c.r. signal voltage is proportional to the number of ions and to the ion radius but is independent of the ion mass. It should also be noted that the rotating electric monopole theory [11], while developed for F.t./i.c.r., is applicable to all i.c.r. spectrometers [11]. It was the single most important theoretical concept needed for the development of F.t./i.c.r.

Conventional i.c.r. spectrometry

In conventional i.c.r. spectrometry [1, 2], a special circuit called a marginal oscillator is used to provide for simultaneous i.c.r. excitation and detection. The magnetic field is scanned to equate successively the ion-cyclotron frequencies with the fixed frequency of the marginal oscillator. Typically, about 20 min is required to scan over a mass range of 15—200 Daltons for a marginal oscillator amplitude of about 10 mV. Normally, the mass linewidth is at least one Dalton throughout the mass spectrum.

FOURIER-TRANSFORM ION-CYCLOTRON RESONANCE SPECTROMETRY

Excitation and detection in F.t./i.c.r.

In the F.t./i.c.r. instrument, all ion masses are excited, essentially at once. This can be accomplished by using a fast frequency sweep from the radiofrequency oscillator [6, 12]. Typically, a frequency sweep from 1 kHz to 1 MHz with an amplitude of a few tens of volts and a sweep time of a few milliseconds will suffice to excite all ions to a cyclotron radius of the order of a centimeter.

While a fast frequency sweep is currently the universally used F.t./i.c.r.

excitation method, pseudostochastic excitation sequences [13] may have more selectivity and may become standard in the future.

Equation 3 and the associated discussion described the generation of an i.c.r. signal voltage from excited i.c.r. motion at a single ion mass. If several ion masses have been excited there will be a composite signal

$$V(t) = \sum_{m} V_m \cos \omega_m t \tag{4}$$

which is just the sum of the individual (Eqn. 3) i.c.r. signals.

Fourier transformation

A Fourier transform (F.t.) is a mathematical recipe which analyzes any complex time signal, such as Eqn. 4, into its constituent frequency components [14]. The analysis can be graphically presented as a plot of amplitude vs. frequency called the frequency spectrum. While the mathematics of Fourier transformation is complex, modern digital computers combined with a special algorithm, called the Fast Fourier Transform [14], give rapid Fourier analysis. With special hardware, called array processors or parallel processors and/or coprocessors, a Fourier transform which analyzes for tens of thousands of individual frequencies can be done in less than a second.

The F.t./i.c.r. cell

The magnetic field constrains ion motion perpendicular to, but not parallel to, the magnetic field. Experiments in i.c.r. require that ions be held in the apparatus for at least a few milliseconds and a static electric field parallel to the magnetic field will complete the ion confinement. A pair of parallel plates called the trapping plates is added to the apparatus of Fig. 1 to create what is called the i.c.r. cell. Application of about 1 V to the trapping plates and 0 V to the other plates of the cell creates an electric potential inside the cell which traps all ions of positive electric charge. Alternatively, negative ions can be trapped with a negative trapping potential. Figure 3 shows the cubic i.c.r. cell [15] which is the most commonly used cell today.

The electric field from the trapping electric potential has a component perpendicular to the cyclotron motion. This component slightly shifts the cyclotron frequencies from those given by Eqn. 1. However, this trapping field shift is well understood [16] and corrections can be made for it.

The F.t./i.c.r. pulse sequence and the F.t./i.c.r. spectrometer

The fundamental principles described above can be combined to create a mass spectrometer as outlined in Fig. 3; the operating pulse sequence is shown in Fig. 4. Not shown in Fig. 3 is the vacuum system which encloses the i.c.r. cell and provides for introduction of the gaseous sample.

Any mass spectrometer converts neutral molecules into gaseous ions, the masses of which are then analyzed. The first step for F.t./i.c.r. operation

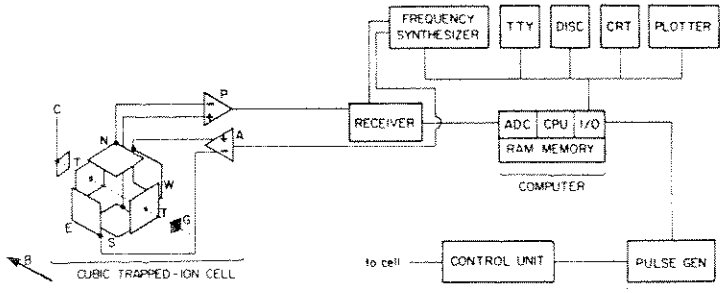

Fig. 3. Block diagram of F.t./i.c.r. spectrometer. The instrument consists of the i.c.r. cell and the associated analog and digital electronics. The cell, which most commonly is cubic in geometry, consists of the transmitter plates, E, W, the receiver plates, N, S, and the trapping plates, T; G and C are the grid and collector for the ionizing electric beam. The computer controls a frequency synthesizer which, via a power amplifier, A, applies the exciting electric field. The i.c.r. signal voltage, Eqn. 4, is amplified by the pre-amplifier, P, and digitized by the analog/digital converter, ADC. The cell is orientated such that the trapping plates are parallel to the magnetic field, B.

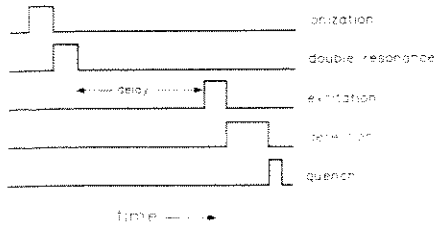

Fig. 4. The F.t./i.c.r. pulse sequence. The pulse sequence is explained in the text.

is thus ionization, which most commonly is achieved by impact on the gaseous neutral molecules by a pulse of high velocity electrons: $M + e^- \rightarrow M^+ + 2e^-$. Other ionization methods, which can have significant advantages, are described below.

The second F.t./i.c.r. pulse, which may be absent, is the double resonance pulse [17]. During this pulse, ions of a particular mass are excited at their cyclotron frequencies. Most commonly, the excitation power is high enough to cause ions to strike the plates of the cell and so be removed. Only one ion mass may be removed or a band of ions may be removed by a high-power frequency sweep. The F.t./i.c.r. third time period, which may be zero, is a delay period to allow for ion/molecule reactions [17, 18]: $M^+ + M \rightarrow$ other ions.

The next pulse is the frequency sweep excitation pulse which excites the cyclotron motion of all ions in the cell. This is followed by the detection time during which the excited cyclotron motion is detected. Finally, a quench pulse is applied to one of the trapping plates of the cell to remove all ions, prior to the start of the next pulse sequence.

The time domain signal (Eqn. 4), containing the signal from each excited ion, is acquired in the computer and is Fourier-transformed to give the frequency spectrum. Alternatively, the time signals from several successive pulse sequences can be added together to form a single time signal of higher signal-to-noise ratio. This is done when the signal-to-noise ratio of a single time signal is too low.

The above pulse sequence is the most rudimentary but also the most commonly used. More complex pulse sequences with added delay times and more pulses have been used for complex ion/molecule reaction studies [18, 19].

Performance

Any mass spectrometric technique can be characterized by the performance criteria of speed, sensitivity, resolution, mass range, convenience and versatility. These individual criteria and other aspects of F.t./i.c.r. are discussed below.

Speed. Instruments for F.t./i.c.r. give the whole mass spectrum in the time which a scanning i.c.r. spectrometer would require to scan across just a single peak in the mass spectrum. For routine mass spectral analysis, the double resonance and reaction delay time periods are set to zero. Typical times for electron-impact ionization, excitation, detection, quench and Fourier transformation would be 5 ms, 5 ms, 10 ms, and 1 ms, repeated 100 times which, with a Fourier transformation time of 1000 ms, gives a total time of about 3 s. This is comparable to the fastest of scanning mass spectrometers and is several thousand times faster than scanning i.c.r. spectrometers.

Sensitivity. Sensitivity can be defined relative to conventional i.c.r. instruments, absolutely in terms of the minimum number of ions detected or absolutely in terms of the partial pressure of or mass of or number of moles of neutral molecules. Instruments for F.t./i.c.r. are, via addition of time signals prior to Fourier transformation, up to 100 times as sensitive as conventional i.c.r. instruments. About 10 ions is the minimum number which can be detected with the current generation of instruments [20].

Partial pressures of 10^{-14} atmospheres of sample have been observed [21] by F.t./i.c.r. Sensitivity measured in terms of the minimum amount of sample required to give a signal, the most important practical definition of sensitivity, indicates that low picogram quantities of sample can be detected [22]. Improvement in this measure of sensitivity can be expected by improvements in the mass transport of the sample to the i.c.r. cell and by optimizing the fraction of neutrals which are converted into ions.

Resolution and mass range. The ultrahigh mass resolution (in excess of 10^6) and the very wide mass range of the F.t./i.c.r. instrument are the two features of the instrument which have most interested the mass spectrometry community. These features were predicted and demonstrated very early in the development of the technique [21, 23–25]. The ultrahigh resolution of the F.t./i.c.r. instrument has been used to measure the precise mass

difference between $^3H^+$ and $^3He^+$ with an accuracy of 3 parts in 10^{11}, for purposes of determining the mass of the electron antineutrino [26, 27].

Frequency, more so than most physical parameters, can be measured to very high accuracy with great ease, with the error of measurement limited only by the inherent uncertainty of the frequency itself. The accuracy with which any frequency can be determined is limited by the classical uncertainty principle, which states that the uncertainty in frequency measurement is inversely proportional to the observation time. Thus, for a 1-s observation of a 1-kHz signal, the uncertainty is 1 Hz or 1 part in 1000. For a 10-s observation, the uncertainty is 0.1 Hz or 1 part in 10 000, and so on. The uncertainty in frequency is manifested in the frequency domain by the finite linewidth of a peak in the spectrum.

At its most fundamental level, an F.t./i.c.r. spectrometer is a "frequency meter", with the "mass meter" feature of the instrument only arising via Eqn. 1. What then determines the uncertainty in measuring cyclotron frequencies? The uncertainty in i.c.r. frequencies is ultimately limited by the duration of the i.c.r. time domain signal. The uncertainty (i.e., the linewidth) can be greater if the signal is observed for less than its duration. The duration of the time signal is limited principally by the background pressure of neutral molecules with the duration being given approximately by

$$\text{Duration (s)} = 2 \times 10^{-8}/\text{pressure (Torr)} \tag{5}$$

Thus, at 10^{-7} Torr, a typical operating pressure, the F.t./i.c.r. time signal will last for 0.2 s. This gives a frequency uncertainty or frequency linewidth of a few Hz.

The F.t./i.c.r. mass linewidth Δm, and the mass resolution $m/\Delta m$ are given, respectively [25], by

$$\Delta m = m^2 \, \Delta\omega/(qB) \tag{6}$$

$$m/\Delta m = qB/(m \, \Delta\omega) \tag{7}$$

where $\Delta\omega$ is the frequency uncertainty. These equations show that mass resolution is directly proportional to the magnetic field and inversely proportional to ion mass. These predictions have been experimentally confirmed [21].

Equation 1 indicates that there is no upper mass limit for F.t./i.c.r. instruments. A more detailed analysis [16] shows that the actual upper mass limit is in excess of 100 000 Daltons. However, a practical limit in most cases is the mass at which the mass linewidth, Eqn. 6, increases to 1 Dalton. For the present generation of instruments with three Tesla magnets, this is about 10 000 Daltons. This upper limit will be raised by the availability of higher field cryomagnets.

While the discussion above involved the "approximate F.t./i.c.r. linewidth", it should be noted that the exact linewidth is known for all circumstances as is the complete F.t./i.c.r. lineshape [28]. The relationship between F.t./i.c.r. linewidths and linewidths for other mass spectrometers is also known [29].

Mass calibration. Calibrating the spectrum is very important in mass spectrometry as the exact mass of a peak can be used to determine molecular formulae. Mass calibration is particularly convenient with F.t./i.c.r. spectrometers as the measurement is one of frequency. This important feature of F.t./i.c.r. was recognized and demonstrated several years ago [21] and has been considerably improved by more accurate corrections [16] for the trapping field shift.

Discrete F.t./i.c.r. spectra

All of the discussion to this point has involved continuous time signals and continuous frequency spectra. Computers, however, deal with numbers and the actual computer data in an F.t./i.c.r. experiment are discrete data. During the detection time period, the continuous time signal, Eqn. 4, is repetitively sampled by an analog-to-digital converter (ADC) to give a series of numbers, each of which is proportional to the instantaneous amplitude of the time signal at the instant of sampling. This series of numbers is the discrete time signal which is stored in the computer. Upon command, the computer performs the numerical Fourier analysis on this discrete time signal and presents the analysis as a second series of numbers which is the discrete frequency spectrum.

There are two important constraints on the acquisition of the discrete time signal. The first is the Nyquist criterion [14] which states that the sampling rate, S, must exceed twice the bandwidth of the spectrum. The second is N, the number of words of available computer memory. These two constraints limit t, the time of observation, commonly called the acquisition time, according to $t = N/S$. As mentioned above, resolution can be limited by the observation time if this is shorter than the signal duration. The equation $t = N/S$ creates a tradeoff between the widest possible mass range and the resolution of the spectrum. There are three methods for obviating this tradeoff. The first is the spectral segment extraction or heterodyne technique [21] which allows ultrahigh-resolution mass spectra over any chosen segment of the mass spectrum. This technique is commonplace today. A second very recent technique is spectral clipping [30], which introduces some distortion but reduces memory requirements. The third and most satisfactory technique is simply to increase the size, N, of the computer memory. Memory costs will continue to decrease for the forseeable future and the tradeoff mentioned above will probably disappear in a few years.

The discrete frequency spectrum given by a numerical Fourier transform is defined only at the $N/2$ discrete frequencies given by $f_i = i/t$ ($i = 0, 1, 2, \ldots, N/2 - 1$). Errors can arise when the continuous frequency $\omega/2\pi$ (Eqn. 1) falls between two frequencies of the discrete spectrum, as it always does. Fortunately, this source of error is understood [31, 32] and the exact frequency and intensity can be evaluated from only the finite number of points in the discrete spectrum.

Pressure requirements

All mass spectrometers operate at high vacuum, typically with pressures in the range 10^{-4}—10^{-6} Torr. It follows then that the sample must have a vapor pressure of at least this much in order to create a gaseous sample to be ionized. Unfortunately, many important compounds have high molecular weights, say above 1000 Daltons, or are polar or charged and, therefore, have negligible vapor pressures at room temperature. While sample heating to temperatures of 200°C suffices for some compounds, many compounds decompose before their vapor pressure reaches even 10^{-4} Torr.

The F.t./i.c.r. spectrometer has some advantage in this regard as the mass spectra can be obtained at sample pressures of 10^{-8} Torr, a pressure 2—4 orders of magnitude lower than that required by other mass spectrometers. Examples are known [33] of samples which decompose just above room temperature but which have vapor pressure at room temperature just sufficient for mass spectral analysis by F.t./i.c.r. but not by other mass spectrometers.

The F.t /i.c.r throughput problem and its solution

As mentioned above, F.t./i.c.r. instruments can give ultrahigh-resolution mass spectra if the background pressure of the sample is ca. 10^{-7} Torr (Eqns. 5 and 7). To keep the background below the 1% level, the residual pressure in the vacuum system should be below 10^{-9} Torr. This residual pressure can be easily reached with modern vacuum technology and a few hours pumping. The pressure dependence of F.t./i.c.r. resolution and mass range requires in general that the pressure, even for low-resolution mass spectrometry, be below 10^{-5} Torr.

The low sample pressures required for high-resolution or high-mass F.t./i.c.r. can be in conflict with other requirements of the experiment. For example, chemical ionization experiments in which the sample is ionized by ion/molecule reaction, require a high pressure of the precursor to the chemical ionizer if the ionization step is to be completed in a reasonable period of time. At a methane pressure of 10^{-5} Torr, formation of the chemical ionizer by the reaction $CH_4^+ + CH_4 \rightarrow CH_5^+$, and chemical ionization via proton transfer to the sample, M, by the reaction $CH_5^+ + M \rightarrow MH^+$, would be complete in 1 s for a sample pressure of 10^{-7} Torr, but high-resolution F.t./i.c.r. spectrometry of MH^+ would be obviated by the high background pressure of methane (Eqns. 5 and 6).

Similarly, the low pressure needed for high-resolution or high-mass F.t./i.c.r. implies evacuation of the previous sample to 10^{-9} Torr and the concomitant pumping period to reach this pressure. The F.t./i.c.r. requirement for low residual pressures, combined with the finite time required to reach these pressures, severely limits the number of samples which can be examined per day. This is the F.t./i.c.r. throughput problem.

In some cases the conflicting pressure requirements for F.t./i.c.r. experiments can be ameliorated by pulsed valve injection of a reagent gas [34, 35].

With pulsed valve injection a short pressure burst of gas is created for rapid ion/molecule reaction, which is then pumped away, allowing high-resolution F.t./i.c.r. spectrometry. These pulsed valve experiments have proven useful for complex ion/molecule studies [34] and for gas chromotography with F.t./i.c.r. [35].

The most complete solution to the throughput problem is achieved by a physical separation of the region where ions are mass-analyzed from the region where ions are created. The simplest apparatus is the Littlejohn-Ghaderi dual cell [36, 37] which has two adjacent cell regions, each like the cell in Fig. 3. A pressure differential of 1000 can be maintained between the two regions by differential pumping of the two halves of the dual cell. Ions which are formed under high pressure conditions in the source region are transferred to the low pressure region by electrical pulses applied to the cell.

The second apparatus which solves the throughput problem consists of a quadrupole mass spectrometer, interfaced to an F.t./i.c.r. spectrometer [38]. The ion source of the quadrupole spectrometer can be operated under conditions optimal for ion formation while the F.t./i.c.r. cell conditions are optimized for ion analysis. Again, differential pumping allows a large pressure drop from the quadrupole source to the i.c.r. cell [38].

Specialized ionization techniques

One of the most important mass spectrometric advances in recent years is the development of specialized techniques for direct ionization into the gas phase from an involatile solid. These techniques have had an enormous impact on the mass spectrometric analysis of involatile biological samples. In each of these techniques a high velocity beam of particles impinges on the involatile solid and in a single operational step volatilizes and ionizes the sample [X + M(solid) → M^+ (gas)]. If X is a fast beam of neutral atoms the technique is called fast atom bombardment (f.a.b.) [39]. If X is a beam of positive ions, the technique is called secondary ion mass spectrometry (s.i.m.s.) [40] and if X is a beam of photons, laser desorption ionization (l.d.i.) [41, 42]. All three techniques are applicable to F.t./i.c.r. instruments [43–45, 38].

APPLICATIONS OF F.T./I.C.R. SPECTROMETRY

Versatility

Conventional i.c.r. spectrometry is the single most versatile technique for examining gas-phase ion chemistry [1, 2]. The ion-cyclotron double resonance technique [1, 2] in particular is the mass spectrometric technique of choice for examining complex ion/molecule reaction pathways. Hundreds of gas phase acidities and basicities have been measured by i.c.r. [46, 47]. Moreover, photon impact experiments such as photodetachment [48] and photodissociation [49] are readily conducted with i.c.r. instruments. Laser

desorption of metal ions provides a general technique for studying metal ion chemistry when the experiments are done on i.c.r. instruments [44]. An important feature of F.t./i.c.r. is that all of the capability of conventional i.c.r. is retained and, moreover, is enhanced by the speed, sensitivity, convenient mass calibration, high resolution and wide mass range of the Fourier approach [21].

The slow speed, low sensitivity, low resolution and limited mass range of conventional i.c.r. instruments, however, has prevented their use as analytical mass spectrometers. The features of conventional i.c.r. combined with the spectroscopic power of the Fourier method, as well as the application on F.t./i.c.r. instruments of recent advances in mass spectrometric ionization techniques, and the development of improved devices for increasing sample throughput, promise to create an ultrahigh-performance analytical mass spectrometer of unparalleled versatility. Some of this versatility is described below. While the various features of F.t./i.c.r. are organized into subsections, each of which gives a brief discussion of a specific feature and leading references, it should be noted that many specific applications of F.t./i.c.r. take advantage of more than one of these specific features of the technique.

Ion/molecule reaction studies

The study of gas-phase ion chemistry was one of the first applications of F.t./i.c.r. to be demonstrated [18]. The wide mass range of the technique and especially the double-resonance technique [17] have been exploited in many laboratories [19, 50—54] for this traditional use of i.c.r.

Ultrahigh-resolution and high-mass applications

The ultrahigh mass resolution and the wide mass range of F.t./i.c.r. are probably the two most important features of the technique. Ultrahigh mass resolution is needed for separating isobaric ions (ions of the same nominal mass) [21, 23, 24] and for determination of molecular formulae [16, 21, 55]. These are "standard" experiments of ultrahigh-resolution mass spectrometers. In addition, ultrahigh mass resolution can be used for exact determination of atomic masses and for determination of the fundamental physical constants of nature [26, 27].

The development of f.a.b., l.d.i. and s.i.m.s. [39—42] for ionization of involatile samples has stimulated considerable interest in the mass spectrometric analysis of high-molecular-weight (say above 1000 Daltons) compounds. The inherent high upper mass limit of F.t./i.c.r. [16, 21, 23—25] makes the technique a prime candidate for the mass spectrometric technique of choice for such high mass analysis [37, 38, 43, 45]. While the most basic theoretical analysis [25] predicts an infinite upper mass limit for F.t./i.c.r., a proper consideration of the components of the trapping field still leaves an upper mass limit above 10^5 Daltons [16].

The types of high-molecular-weight compounds which will be analyzed by F.t./i.c.r. are limited only by the imaginations of users. Compounds of

biological origin such as proteins, polysaccharides, and polynucleotides, polymers, high-molecular-weight organic and organometallic compounds, complex substances such as rubbers and plastics will all be analyzed mass spectrometrically by F.t./i.c.r. [37, 38, 43, 45].

It should be noted that the mass resolution and mass range of the F.t./i.c.r. instrument are critically dependent on both computer technology and magnet technology. The performance/price ratio for both computers and cryomagnets increases each year and it follows that F.t./i.c.r. performance can be expected to improve steadily in the future. In this respect, F.t./i.c.r. differs from both quadrupole and magnetic sector mass spectrometers, both of which are based upon mature technologies.

Experiments with m.s./m.s.

A general technique for analysis of gas-phase ions is the so-called m.s./m.s. experiment in which an ion is mass-selected out of an ensemble of ions, accelerated to high velocity and collided with a suitable gas. The collision induces the ion to fragment and the mass spectrum of the collision products is characteristic of the structure of the original ion [56]. The experiment requires two mass spectrometers; one to select the first ion and one to analyze the collision products.

The experiment can be done with just a single F.t./i.c.r. instrument by adding the requisite pulses and delays to the pulse sequence [34, 37, 50, 57, 58]. After i.c.r. ejection of all ions but the desired ion, the desired ion is excited by double resonance such that its orbital radius is just less than the cell dimensions. Then, the ion is allowed to undergo high energy collisions with the collision gas. Finally, the gas is pumped away and the mass spectrum of the collision fragments is obtained by the normal F.t./i.c.r. excitation-detection sequence.

Gas chromatography/F.t./i.c.r.

A most powerful general analytical tool is the composite instrument formed from a gas chromatograph and a mass spectrometer. The high separation power of a capillary-column gas chromatograph combined with the high performance of an F.t./i.c.r. spectrometer gives an analytical instrument with many applications for mixture analysis [59, 22, 37, 60].

The F.t./i.c.r. instrument is a pulsed technique and as such is particularly well suited for g.c./m.s. applications. Electron-impact mass spectra can be obtained from (say 10 ms) temporal slices of a g.c. peak, with each mass spectrum being representative of a slice. In contrast, conventional scanning mass spectrometers have a scan time comparable to the temporal width of a g.c. peak. With a conventional scanning mass spectrometer, different parts of the mass spectrum then correspond to different parts of the g.c. peak. If the g.c. peak consisted of several partially separated components, the single mass spectrum from a scanning mass spectrometer would be related to the components in a complex and indeterminate manner. In contrast, F.t./i.c.r.

mass analysis of the same g.c. peak would show several different mass spectra which would indicate the partial separation in the g.c. peak.

At first, it might appear that the low pressure requirements of F.t./i.c.r. and the gas load from the g.c. barrier gas would make an F.t./i.c.r. instrument an unsuitable mass spectrometer for gas chromatography/mass spectrometry. However, by careful control of the g.c. flow rate and pumping speed [59], the use of pulsed valve injection of the effluent [22, 60] and the use of the dual cell [36, 37], high-sensitivity, high-mass resolution g.c./F.t./i.c.r. results can be obtained.

Photodissociation experiments and surface analysis

One of the traditional i.c.r. experiments which profits from the wide mass range of the F.t./i.c.r. experiment is the photodissociation experiment [49]. In this experiment ions are fragmented by photon impact: $h\nu + M^+ \rightarrow M_1^+, M_2^+, \ldots$. The photodissociation spectrum obtained by plotting the abundance of M^+ vs. photon wavelength and the photofragment mass spectrum are diagnostic of the structure of M^+. These experiments provide complementary structural information to the m.s./m.s. experiment. The experiments are readily performed on F.t./i.c.r. instruments [50, 61, 62]. At high mass, momentum conservation limits the amount of kinetic energy which is available for m.s./m.s.-induced fragmentation and photodissociation experiments may prove particularly valuable for structural analysis of high mass ions [62].

A novel use of F.t./i.c.r. is to analyze the components adsorbed on a surface. The technique is to desorb the surface components by pulsed laser heating and then ionize and mass analyze desorbed components by F.t./i.c.r. [63].

FUTURE DEVELOPMENTS

More detail regarding the topics mentioned above can be found in other articles in this issue. These articles also contain many leading references to the F.t./i.c.r. literature. Also noteworthy are recent review articles [64—66] which cover similar material to that in this article, but from the viewpoints of different authors.

Resolution and mass range in F.t./i.c.r. are dependent upon both magnet and computer performance and one can expect F.t./i.c.r. performance to follow the steadily increasing performance/price ratio of computers and cryomagnets. The results to date on solving the "throughput problem" [36—38] are only the first attempts and it is reasonable to expect considerable improvements in the future. Sensitivity will be improved by more efficient ionization schemes such as multiphoton ionization [22] which gives more complete conversion of the neutral sample into ions. Larger i.c.r. cells [67] will increase the sensitivity because of the larger number of ions which can be held in the cell (Eqn. 3).

New data handling methods [13, 30, 68, 69] will allow the maximum amount of spectral information to be extracted from the available discrete F.t./i.c.r. data. Finally, the specific chemical problems to which F.t./i.c.r. will be applied is limited only by the imaginations of the users and the versatility of the technique ensures that there are many new applications yet to be demonstrated.

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