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(54) Method of operating an ion trap mass spectrometer.

(57) A method of operating an ion trap mass spectrometer comprises generating a three dimensional trapping field with DC and/or RF voltages applied to an ion trap structure to trap ions over a predetermined mass-to-charge range, scanning the DC and/or RF voltages to sequentially eject ions over said range and simultaneously applying a supplementary AC voltage to generate an AC field to more effectively eject said ions.

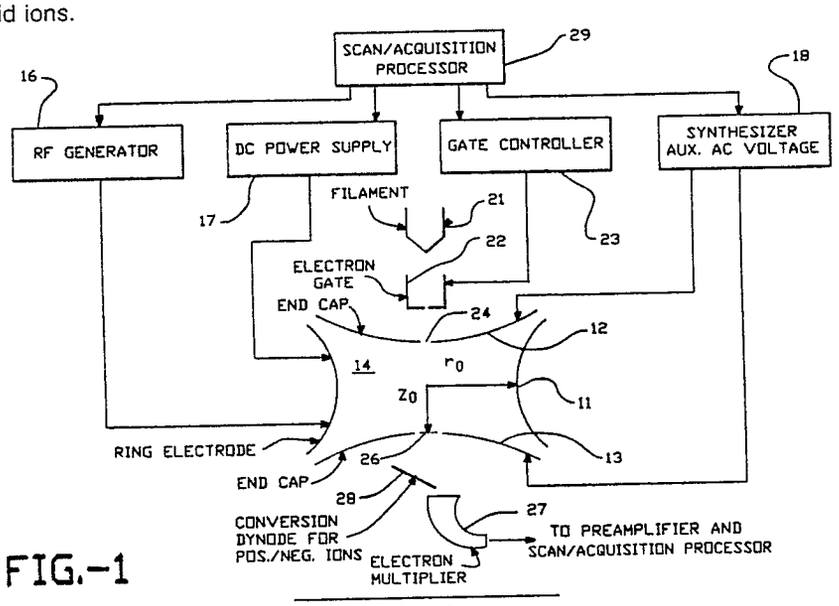

FIG.-1

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METHOD OF OPERATING AN ION TRAP MASS SPECTROMETER

This invention relates to a method of operating an ion trap mass spectrometer.

Ion trap mass spectrometers or quadrupole ion stores have been known for many years and described by a number of authors. They are devices in which ions are formed and contained within a physical structure by means of hyperbolic electrostatic RF and/or DC fields. In general, RF and/or DC voltages are applied to hyperbolic or spheric electrode structures which define the trapping volume into which the trapping fields extend. The structure generally comprises a ring electrode with spaced end caps.

Mass storage is generally achieved by operating the trap electrodes with values of RF voltage V and its frequency f. DC voltage U and device size r_0 such that ions having their mass-to-charge ratios (M/Z) within a finite range are stably trapped within the electrostatic fields. The aforementioned parameters are sometimes referred to as the scanning parameters and have a fixed relationship to the mass-to-charge ratios of the charged ions. For trapped ions there is a distinctive characteristic frequency for each value of mass-to-charge ratio. In one ion detection method, the characteristic frequencies can be determined by a tuned circuit which couples to the oscillating motions of the ions within the trap. Such a method has been difficult to implement and yields poor resolution and limited mass range.

In US-A-4540884 there is described a method of operating an ion trap in the mass selective instability mode. The mass selection is achieved by simultaneously trapping ions within a mass range of interest and then scanning the applied RF and/or DC voltages or the frequency of the RF voltage to sequentially render unstable trapped ions of consecutive specific masses. The unstable ions flow out through apertures in an end cap to a high gain electron multiplier to provide signals indicative of the ion mass.

In US-A-4540884 there is described an improvement to such method of operating an ion trap mass spectrometer, which includes the additional step of applying to the trap a supplementary AC voltage which generates a field which cooperates with the trapping fields in the ejection of ions from the ion trap trapping volume.

According to this invention there is provided a method of operating an ion trap mass spectrometer to render ions within a predetermined range of mass-to-charge ratios trapped in a three-dimensional trapping field generated by a fundamental RF voltage sequentially unstable, comprising the steps of varying the fundamental RF voltage to eject ions of sequential mass-to-charge ratios; and simultaneously applying a supplementary AC voltage at a lower frequency to generate a supplementary field whereby the ions of sequential mass-to-charge ratios are more effectively ejected.

We have found that if the suplemental voltage is set at a frequency lower, for example about half, the frequency of the RF voltage, the sensitivity and resolution of the ion trap mass spectrometer can be significantly improved when the ion trap is operated in the mass-selective instability mode.

Thus, the invention provides a method of operating an ion trap mass spectrometer, which permits the storage of a large number of ions to improved sensitivity while providing the good resolution.

The invention will now be described by way of example with reference to the drawings, in which:

Figure 1 is a schematic diagram of an ion trap mass spectrometer;

Figures 2A to 2D show the scan functions for an EI and a CI analysis;

Figure 3 shows the stability diagram of a quadrupole ion trap;

Figures 4A and 4B show the improvement in resolution obtained with the method of the invention in a scan of FC43; and

Figures 5A and 5B show the improvement in resolution obtained with the method of the invention in a scan of hexachlorobenzene.

A three-dimensional ion trap mass spectrometer is schematically illustrated in Figure 1. The ion trap includes a ring electrode 11 and two spaced end caps 12 and 13 facing each other. The ring electrode and end caps define a trapping volume 14 having a radius r_0 and a vertical dimension z_0. An RF voltage generator 16 is connected to the ring electrode 11 to supply a radio frequency voltage v sin t (the fundamental voltage) between the end caps and the ring electrode which provides the quadrupole filed for trapping ions within the ion storage volume 14. A DC voltage U from power supply 17 may also be applied to the trap electrodes.

A supplementary AC voltage generator 18 is coupled to the end caps 12 and 13 to supply a voltage v_2 sin t. Means are provided for projecting an ionizing electron beam into the ion volume 16. The electron source comprises a filament 21 fed by a filament power supply, not shown, and a cylindrical electron gate electrode 22 having a control voltage applied by gate controller 23 to turn the electron beam on and off as desired for ionizing sample within the trapping volume. The end cap 12 includes an axial aperture 24 through which the

electron beam projects. The opposite end cap 13 is perforated 26 to allow unstable ions in the fields of the ion trap to exit and be detected by the electron multiplier 27. Conversion dynode 28 is disposed to receive the ejected ions and operates as described in US-A-4423324. The output signal is amplified and applied to processor 29 which not only serves to process the signal and provide a mass spectrum, but also controls operation of the RF, DC and supplemental voltage power supplies and the gate controller to perform an analysis.

EI and CI scans are shown in Figure 2A-2B. The EI scan is shown by a solid line while the CI scan is shown by the dotted line. In the EI scan, the fundamental RF voltage and DC voltage applied to the ring electrode is selected to store only sample ions of a mass range of interest, A. The sample is introduced in the trapping volume and electron gate voltage is applied to permit the electron beam to enter the volume and ionize the sample. The RF voltage is then ramped to the point B to select the mass range of interest and then the voltage is increased, C, to scan. The scan spectrum is shown in Figure 2C.

In the CI mode, the voltages are fixed for the period A′ during which the reagent is ionized with reagent ions. The voltage is increased, B′, and the reagent ions then react with neutral sample molecules and form sample ions. Then the voltage is increased, C′, to select the low mass for start of the scan. The voltage is ramped, D′, to provide the scan spectrum shown in Figure D.

In operation of the ion trap in the MS/MS mode, ions are formed in the trap volume 16 while maintaining DC and RF voltages so as to store the selected mass range. The trapping voltages are then reduced in such a way that only stable ions of interest are retained at which time a dissociation step is carried on in which the ions of interest are caused to collide with a gas or surface so as to fragment. Since the ions to be fragmented may or may not have sufficient energy to undergo fragmentation by collision with the gas or surface, it may be necessary to pump energy into the ions of interest to cause them to collide with energetic or excited neutral species so the system will contain enough energy to cause fragmentation of the ions of interest. The fragmented ions are then swept from the trap by varying the RF voltage and a scan of the mass spectra is obtained.

Any known way of producing energetic neutral species may be used in the preceding step. Excited neutrals of Argon of Xenon may be introduced from a gun, pulsed at a proper time. A discharge source may be used. A laser pulse may be used to pump energy into the system either through ions or through the neutral species.

The scanning step in which the ions become sequentially unstable, leave the trap volume and are detected, is accompanied by the application of a supplemental AC voltage to generate fields in the axial direction. The supplemental voltage is applied to both of the end caps or to one of the end caps while the other end cap is grounded. The supplemental AC voltage is preferably selected to have a frequency which is approximately one-half the frequency of the fundamental RF voltage and which causes the trapped ions near the instability boundary to oscillate in the axial direction. This oscillation is the characteristic frequency of ion motion in the z or axial direction and close to the point where the ions become unstable during the mass scan. The frequency of ion motion in the z direction is determined by the β_z Parameter and can be calculated by multiplying β_z by the RF drive frequency and dividing the value by 2. That is, $f = \beta_z \times 1/2\ f_{RF}$ β_z itself can be calculated using the a and q parameters of the stability diagram, Figure 3. Excitation of the ions near the stability boundary where β_z is close to 1 leads to more uniform ejection, that is, all ions of the same m/z value are ejected during a short time interval. This results in resolution improvements.

Figure 4A shows part of the mass spectrum for FC 43, a calibration compound with prominent peaks at m/z 69 and m/z 100. Other mass peaks originate from background in a mass spectrometer. Filament emission current for the experiment was set at 30 microamps and the ionization time was 1.5 msec. A helium buffer gas was present at a pressure of approximately 1×10^{-3} torr. The lack of resolution and peak broadening indicates that the ejection of some ions at a given m/z is extended. That is, some ions are ejected too late and are not resolved from ions of subsequent m/z value. Figure 4B shows the mass spectrum acquired with the exitation voltage turned on during the mass scan at a fixed frequency of 530 KHz and a fixed amplitude of 5 volts. It is noted that the resolution is much improved and that the resolution improvement is observed over the entire mass range of the ion trap. The data shown in Figure 4B was for the exitation voltage being applied only during the analysis scan. Similar results were obtained with the exitation voltage continuously applied. The new scanning mode has been characterised across a wide range of frequencies and amplitudes. Amplitudes were between 1 and 10 volts, frequency between 300 KHz and 600 KHZ. At frequencies significantly below half the RF drive frequency, ions are ejected at a value of the q parameter less than 0.91, i.e., at a point where less RF voltage is required. This results in an increase of the mass range of the ion trap mass spectrometer. At frequencies higher than the RF frequency, similar effects are observed. This is believed to be

because of harmonics of the ion motions are found symmetrically around the $_z$ = 1 value.

5A shows the mass spectrum of m/z 284, a characteristic ion, from a GC/MS run of a 10 pg hexachlorobenzene sample in the prior mode of ion trap operation.

Figure 5B is the mass spectrum of same sample using the new mode of operation.

Thus, there has been provided a method of operating an ion trap mass spectrometer with improved resolution and sensitivity.

Claims

1. A method of operating an ion trap mass spectrometer to render ions within a predetermined range of mass-to-charge ratios trapped in a three-dimensional trapping field generated by a fundamental RF voltage sequentially unstable, comprising the steps of varying the fundamental RF voltage to eject ions of sequential mass-to-charge ratios; and simultaneously applying a supplementary AC voltage at a lower frequency to generate a supplementary field whereby the ions of sequential mass-to-charge ratios are more effectively ejected.

2. A method as claimed in Claim 1, in which the trapping field is generated using a combinaton of RF and DC voltages and magnetic fields.

3. A method of operating an ion trap mass spectrometer with fundamental DC voltage and/or RF voltage applied thereto to generate a trapping field to trap ions over a predetermined mass-to-charge ratio range, comprising the steps of scanning the fundamental RF voltage and/or DC voltage whereby ions over said predetermined mass-to-charge ratio range are sequentially ejected from the ion trap; and simultaneously applying a supplementary AC voltage at a lower frequency to generate a supplementary field whereby ions of particular mass-to-charge ratios are more effectively ejected.

4. A method as claimed in any preceding claim, in which the supplementary AC voltage is set at a fixed frequency and amplitude.

5. A method as claimed in any preceding claim, in which the supplementary AC frequency and/or amplitude are varied.

6. A method as claimed in any preceding claim, in which the supplementary AC voltage has a frequency within plus or minus twenty percent of half the fundamental RF frequency.

7. A method as claimed in any preceding claim, in which ions are created inside the trap.

8. A method as claimed in any one of Claims 1 to 6, in which externally created ions are injected into the trap.

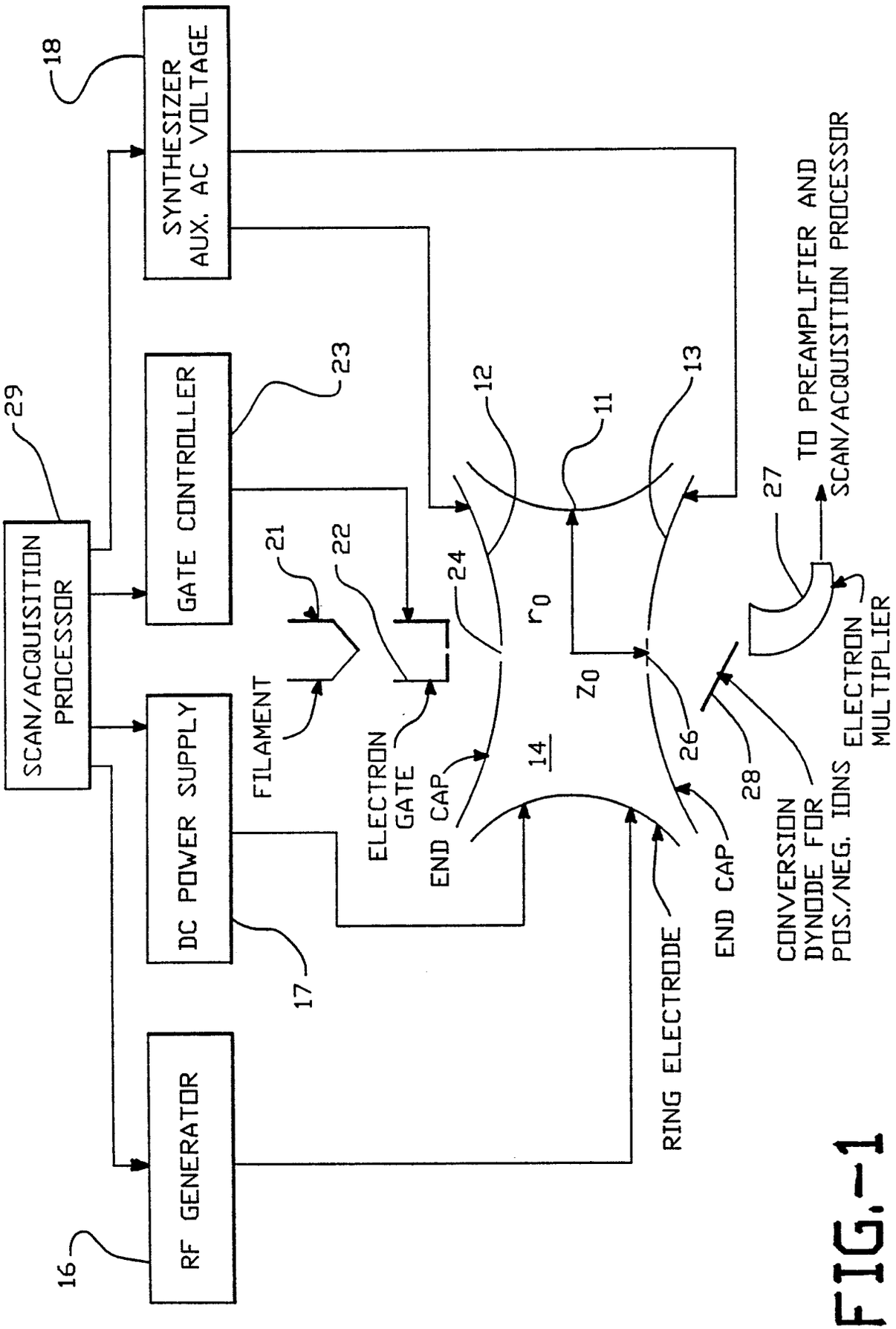

SYNTHESIZER AUX. AC VOLTAGE
18
GATE CONTROLLER
23
SCAN/ACQUISITION PROCESSOR
29
DC POWER SUPPLY
RF GENERATOR
16
17
FILAMENT
21
22
ELECTRON GATE
END CAP
24
12
11
13
r_0
z_0
14
RING ELECTRODE
END CAP
26
28
27
CONVERSION DYNODE FOR POS./NEG. IONS
ELECTRON MULTIPLIER
TO PREAMPLIFIER AND SCAN/ACQUISITION PROCESSOR

FIG.-1

FIG.-2A

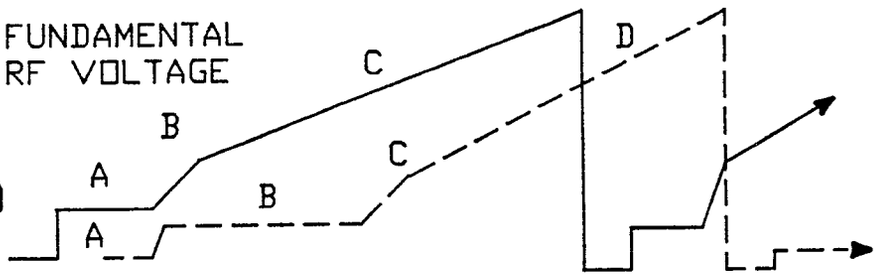


FIG.-2B

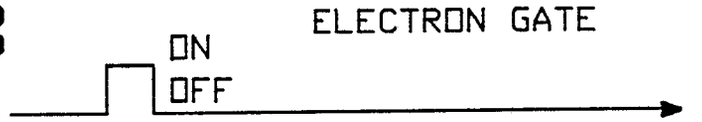


FIG.-2C

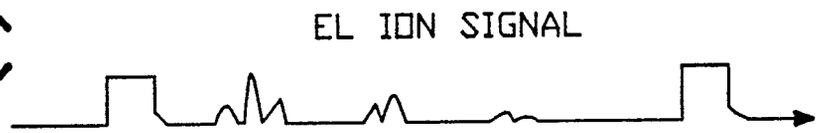
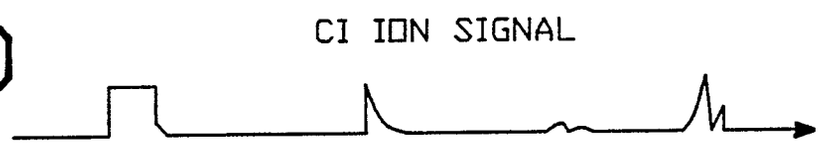


FIG.-2D



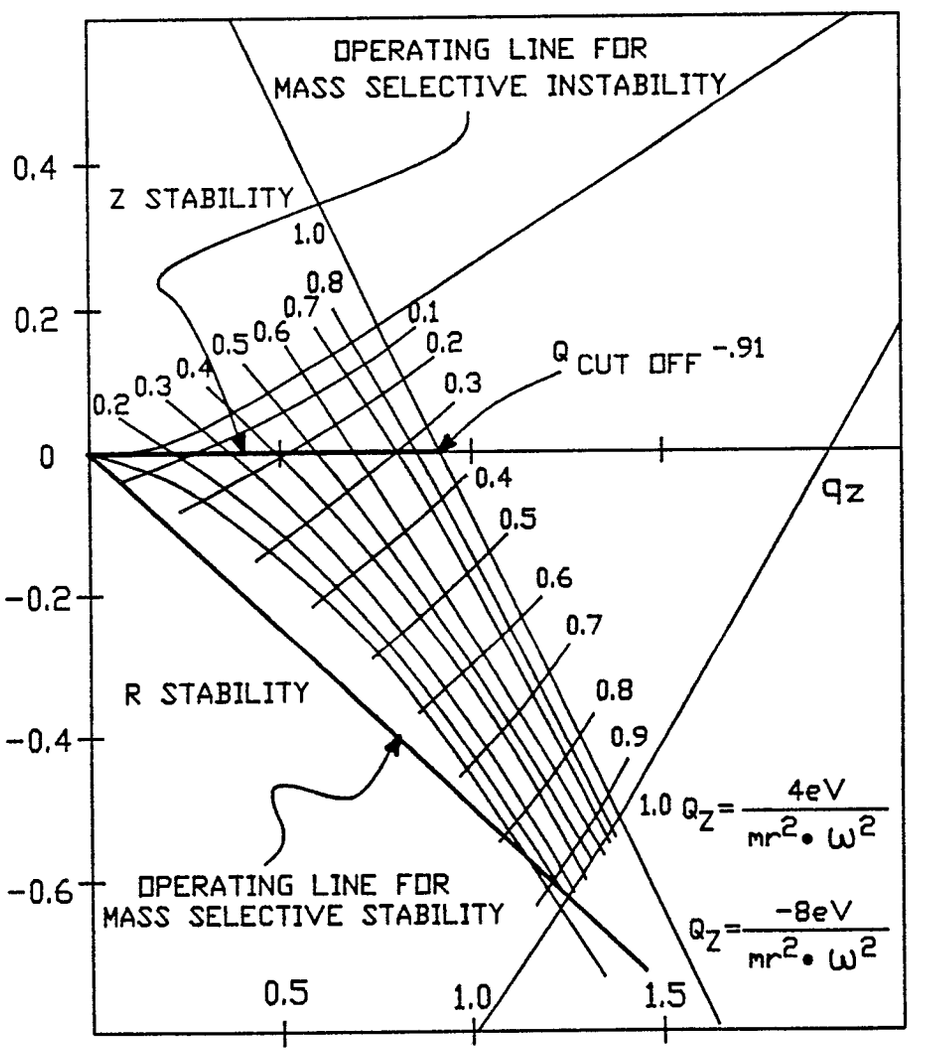


FIG.-3

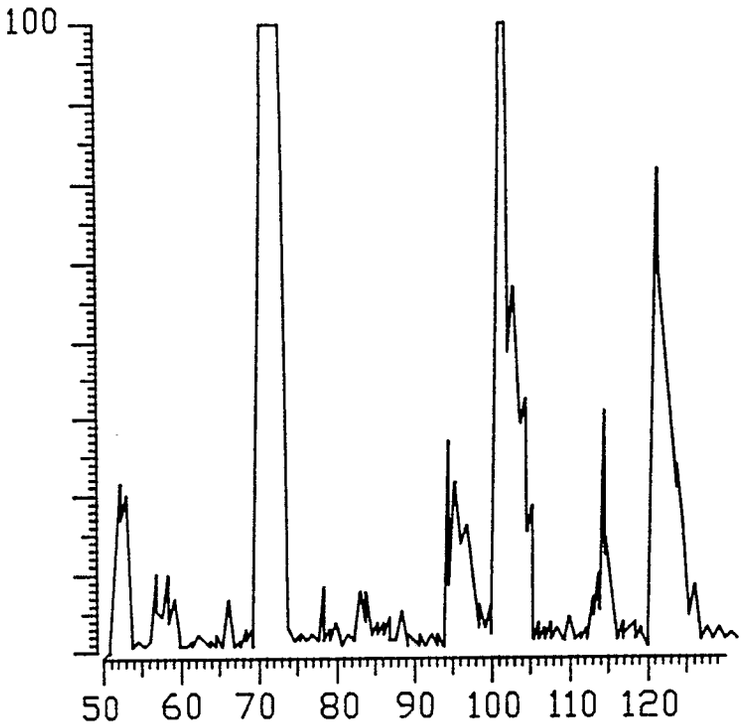


FIG.-4A

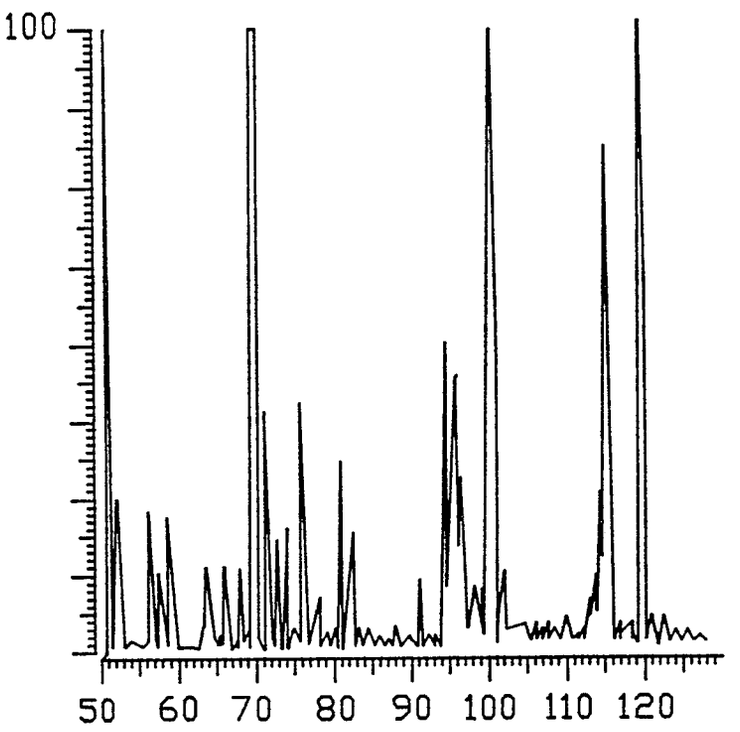


FIG.-4B

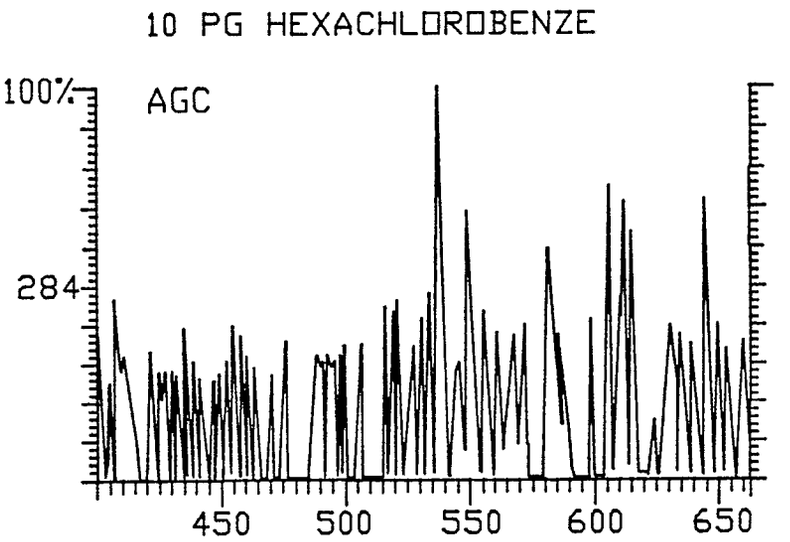

10 PG HEXACHLOROBENZE
AGC
100%
284
450
500
550
600
650

FIG.-5A

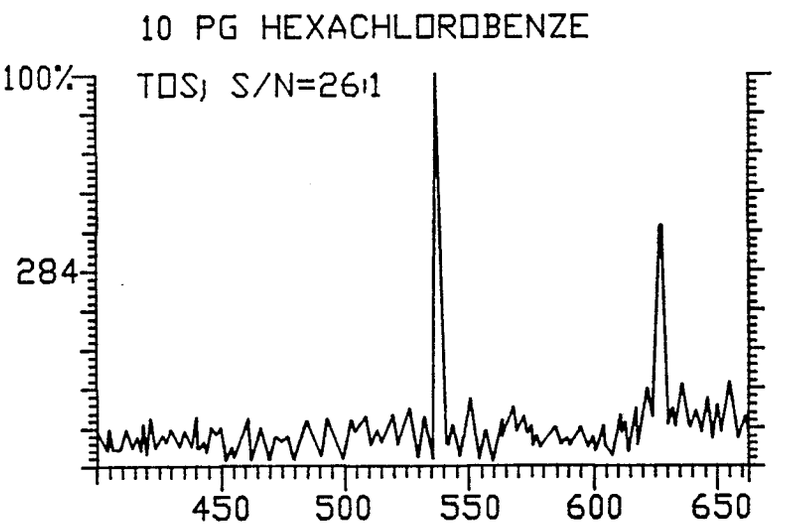

10 PG HEXACHLOROBENZE
TOSJ S/N=261
100%
284
450
500
550
600
650

FIG.-5B

SUPPLEMENTARY

European Patent Office

PARTIAL EUROPEAN SEARCH REPORT

which under Rule 45 of the European Patent Convention shall be considered, for the purposes of subsequent proceedings, as the European search report

Application number
EP 89 30 5618

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X	EP-A-0 202 943 (FINNIGAN) * Figure 1; page 3, line 33 - page 4, line 1; page 4, lines 18-21; page 8, lines 14-25; page 9, line 19 - page 10, line 6 * --	1,3-7	H 01 J 49/42
X	INTERNATIONAL JOURNAL OF MASS SPECTROMETRY AND ION PROCESSES, vol. 60, no. 1, September 1984, pages 85-98, Elsevier, Amsterdam,NL G.C. STAFFORD et al.: "Recent improvements in and analytical applications of advanced ion trap technology" * Page 85, lines 13-21; page 90, "Mass analysis by mass selective instability"; figure 1; page 92, lines 36-38 * --	1,3,4, 6,7	
X	EP-A-0 262 928 (FINNIGAN) * Page 2, lines 14-17; page 2, lines 23-24; page 6, lines 19-23; page 6, lines 61-64 ; ... /	1-8	TECHNICAL FIELDS SEARCHED (Int. Cl.4) H 01 J

INCOMPLETE SEARCH

The Search Division considers that the present European patent application does not comply with the provisions of the European Patent Convention to such an extent that it is not possible to carry out a meaningful search into the state of the art on the basis of some of the claims.

Claims searched completely: 1,3
Claims searched incompletely: 2,4-8
Claims not searched:
Reason for the limitation of the search:
The magnetic field of claim 2 is not mentioned in the description or drawings. From claim 2 alone it is not clear, what way the magnetic field is used to confine (or to help confining) ions. Normally, quistors of the type described don't use an additional magnetic field.

Place of search	Date of completion of the search	Examiner
The Hague	26-09-1989	FRITZ

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO Form 1505.1 03.82

DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
	page 8, line 65 - page 9, line 5; page 10, lines 32-47 *		
	--		
X,P	US-A-4 749 860 (KELLEY et al.)		
	* Figure 1; column 2, lines 9-21; column 3, lines 20-29 *	1,3-7	
	--		
Y	US-A-2 950 389 (W. PAUL et al.)		
	* Whole document *	1,3-8	
	--		
Y,D	EP-A-0 113 207 (FINNIGAN)		TECHNICAL FIELDS SEARCHED (Int Cl.4)
	* Whole document *	1,3-8	
