ABSTRACT

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Advances in High Field Asymmetric Ion Mobility Spectrometry (FAIMS) Analyzers and FAIMS-Mass Spectrometry Interfaces

(Under the direction of Dr. Gary L. Glish)

High field asymmetric ion mobility spectrometry (FAIMS) is a gas phase separation technique that separates ions by the ratio of high to low electric field mobility, which is a characteristic of the three dimensional structure of ions. FAIMS separation in front of mass spectrometric analysis has the ability to reduce chemical noise thereby increasing signal-to-noise ratios and limits of detection; it can also be used to separate isobaric and isomeric compounds. FAIMS analyzers are simple to construct and are easily integrated into the atmospheric pressure ion source of current mass spectrometers without major modifications. The motivation of developing FAIMS analyzers in the Glish lab has been for the study of three dimensional gas phase ion structure of biological molecules, as well as to improve separation of compounds which are irresolvable using low resolution mass spectrometry and liquid chromatography. This dissertation does not focus on the application of FAIMS for structural elucidation, but instead on the development of a FAIMS device that combines excellent speed, resolution, and sensitivity in a simple to use small package. Described in the following chapters are the background for selection of gas phase ions by shape-to-charge, the development of a high amplitude asymmetric waveform power supply, modifications made the planar FAIMS device designed by the Pacific Northwest National Lab and the development of four generations of planar FAIMS devices. For each device limitations and flaws in the design are discussed along with proposed solutions and data demonstrating the results of modifications to analyzer design, and the successful construction of a planar FAIMS device with high speed, high sensitivity, and resolving power equal to much larger and more expensive devices.

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LIST OF ABBREVIATIONS AND SYMBOLS

3D	three dimensional
A	Ampere
a	acceleration
Å	Angstrom; (10^{-10} meters).
Ar	Argon
AWG	American wire gauge; a measure of wire thickness
BNC	Bayonet Neill-Concelman; a bayonet style electrical connection
BSA	bovine serum albumin
C	capacitance
CID	collision induced dissociation
cm	centimeter
CO_2	carbon dioxide
CV	compensation voltage
CV_{peak}	value of compensation voltage at center of analyte peak
ΔCV_{FWHM}	width of peak in compensation voltage scan at full width half maximum
D	diffusion coefficient
D_{II}	diffusion coefficient parallel to the analytic gap in FAIMS
d_h	distance traveled by an ion during the E_h
d_l	distance traveled by an ion during E_l
Da	Dalton; unit of mass equal to 1 atomic mass unit
dc	direct current
DV	dispersion voltage

D_z	potential well depth for ions stored in an ion trap
E	electric field strength
e	fundamental charge constant; equal to $1.602e^{-19}$ coulombs/mole
E_h	electric field during high field portion of an asymmetric waveform
E_l	electric field during low field portion of an asymmetric waveform
E/N	electric field divided by gas number density
$E/N_{critical}$	E/N at which ions begin to deviate from low field conditions
ECD	electron capture dissociation
E_{com}	center of mass collision energy
E_{lab}	laboratory frame collision energy
ESI	electrospray ionization
eV	electron volt; unit of energy equal to $1.602e^{-19}$ joules
F	force
f	high frequency sinusoidal wave used to construct asymmetric waveform
FET	field effect transistor
G1	first generation FAIMS developed in UNC-Bruker collaboration
G2	second generation FAIMS developed in UNC-Bruker collaboration
G3	third generation FAIMS developed in UNC-Bruker collaboration
G4	forth generation FAIMS developed in UNC-Bruker collaboration
g	the distance between two parallel FAIMS electrodes
g_{opt}	optimum FAIMS analytical gap width for a ratio of K_h/K_l
g_e	effective gap width for specific mobility ion
F	force

F_3	form factor coefficient for a FAIMS waveform
f	frequency
FAIMS	high field asymmetric waveform ion mobility spectrometry
FT-ICR	Fourier transform ion cyclotron resonance mass spectrometer
FWHM	full width at half maximum
GC	gas chromatography
GC/MS	gas chromatography coupled with mass spectrometry
H/D exchange	hydrogen deuterium exchange mass spectrometry
He	helium
Hz	Hertz; unit of frequency equal to 1 cycle per second
i	current
ICC	ion current control
IMS	ion mobility spectrometry
IMS-MS	ion mobility spectrometry coupled with mass spectrometry
IR	infrared
IRMPD	infrared multiphoton dissociation
K	mobility
K_0	reduced mobility; corrected for temperature and pressure
K	Kelvin; unit of temperature
k_b	Boltzmann's constant $1.38e^{-23}$ J/K
kDa	kiloDalton; $1e^{3}$ Da
kHz	kiloHertz; $1e^{3}$ Hz
K_h	mobility during the high electric field portion of FAIMS waveform

K_l	mobility during the low electric field portion of FAIMS waveform
kV	kilovolt
L	inductance
L	drift tube length
LC	liquid chromatography
LC/MS	liquid chromatography coupled with mass spectrometry
m	meter
m	mass
m/z	mass-to-charge ration
m_1	mass of ion
m_2	mass of neutral molecule
MHz	MegaHertz; 1e^{6} Hz
mm	millimeter
mTorr	unit of pressure; 1e^{-3} Torr
MOSFET	metal-oxide-semiconductor field effect transistor
MS	mass spectrometry
ms	millisecond
MS/MS	tandem mass spectrometry
MΩ	megaOhms
N	number density
N_2	nitrogen
NMR	nuclear magnetic resonance
ns	nano seconds; 1e^{-9} seconds

P	pressure in Torr
pA	pico Ampere = 1e^{-12} Amperes
PCB	printed circuit board
PEEK	polyetherertherketone
pf	pico Farad; unit of capacitance
p-FAIMS	planar FAIMS
PNNL	Pacific Northwest National Labs
q	charge
q_z	Mathieu stability parameter for an ion in the z dimension
Q-TOF	hybrid mass spectrometer coupling a linear quadrupole and time of flight
R	resolving power
r_0	radial dimension of an rf ion trap
rf	radio frequency
RLC	resonant circuit using inductance and capacitance
RSD	relative standard deviation
s	seconds
SF_6	sulfur-hexafluoride
S/N	signal to noise ratio
T	temperature
t	time
“T” connection	an electric connector with three equal potential fittings.
ΔT	difference in temperature between two points
t_d	drift time

t_{DV}	duration of the dispersion voltage
t_h	duration of the high field portion of FAIMS waveform
t_l	duration of the low field portion of FAIMS waveform
TOF	time of flight (a type of mass analyzer)
Torr	unit of pressure (760 Torr = 1 atm)
TTL	transistor transistor logic; high/low logic consisting of 0 or 5 V amplitude
t_{res}	time an ion spends in the analytical gap of a FAIMS analyzer
U	a standard height of rack mounted electronics enclosure
UNC	University of North Carolina
V	Voltage
$\mathrm{V_{0\text{-}peak}}$	Voltage of waveform measured from 0 V to maximum amplitude
$\mathrm{V_{cc}}$	voltage between ground and the collector of a bipolar junction transistor
v_d	ion drift velocity
$V_{peak\text{-}to\text{-}peak}$	Voltage amplitude measured from peak to peak of an AC signal
W	Watt; unit of power; 1 Joule per second
z	charge
$\mathrm{z_0}$	dimensions of an ion trap in the z direction
$\Delta\mathrm{F}$	correctional form factor used to correct for no idea FAIMS waveforms
μF	micro Farad; unit of capacitance
π	3.14
Ω	drive frequency for rf ion traps
Ω_{avg}	orientationally averaged collision cross section
Φ	phase shift between two sinusoidal waveforms

ω	frequency of sinusoidal waveform in radians/second
°C	temperature on the Celsius scale