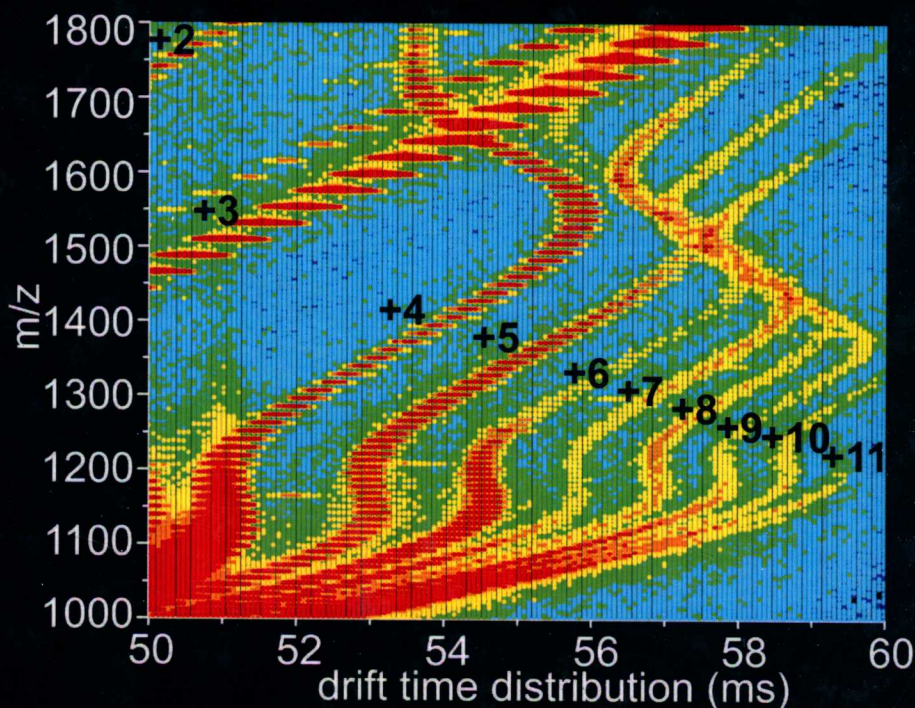


Ion Mobility Spectrometry- Mass Spectrometry

Theory and Applications



Edited by

Charles L. Wilkins and Sarah Trimpin



CRC Press
Taylor & Francis Group

Ion Mobility Spectrometry- Mass Spectrometry

Theory and Applications

Edited by

Charles L. Wilkins

Sarah Trimpin



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2011 by Taylor and Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number: 978-1-4398-1324-9 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Ion mobility spectrometry-mass spectrometry : theory and applications / edited by
Charles L. Wilkins, Sarah Trimpin.
p. cm.

Includes bibliographical references and index.

ISBN 978-1-4398-1324-9 (hardcover, includes cd-rom : alk. paper)

1. Ion mobility spectroscopy. 2. Mass spectrometry. I. Wilkins, Charles L. (Charles Lee), 1938- II. Trimpin, Sarah. III. Title.

QD96.P62I56 2011
543'.65--dc22

2010038209

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Edited by
Charles L. Wilkins
Sarah Trimpin

Ion Mobility Spectrometry- Mass Spectrometry

Theory and Applications

Preface

Rapid advances in ion mobility spectrometry–mass spectrometry (IMS-MS) are beginning to have significant impact on biological and materials research and in analytical laboratories worldwide. Although the history of ion mobility spectrometry goes back at least 40 years, when it was more commonly known as plasma chromatography, the more recent hyphenation of ion mobility with mass spectrometers has greatly expanded its scope. Thus, IMS is a gas-phase separation method that is applicable for a wide variety of substances. For example, many airport explosives detectors are currently based upon IMS. However, it can also be used for biomedical applications, such as understanding the factors associated with Alzheimer's disease or cancer, as will be seen in several of the chapters.

Introduction of more or less turnkey commercial IMS-MS instruments are just now making this technology generally available. The analytical power afforded by IMS-MS instruments is certain to drive the technology from research to analytical laboratories. Thus, this book appears at a critical time and presents contributions from developers, as well as more recent users of this technology. It is a goal of this work to provide key information in a single location to help readers appreciate the value of having molecular size and shape information combined with the well-known analytical advantages of high-performance mass spectrometry. Armed with this understanding, it is expected that some of the readers will develop sufficient appreciation of the possible analytical uses of IMS-MS that they will become interested in further exploring the power of the method.

To this end, both fundamentals and applications are presented. Accordingly, the book begins with an overview chapter and fundamentals (Chapters 1 to 3) followed by sections emphasizing instrumentation (Chapters 4 to 7) and ionization sources (Chapters 8 and 9). In the subsequent applications (Chapters 10 to 16), homebuilt and commercial instrumentation using electrospray ionization and matrix-assisted laser desorption/ionization methods are employed to solve biological and synthetic motivated questions. In this way, it is the intent of the editors to cover the current status of IMS-MS in such a way as to make it convenient for those readers unacquainted with this technique to understand its fundamental theory and practical applications. As a consequence, it is expected that this volume could serve as a useful specialized textbook for an advanced course on IMS-MS.

Sarah Trimpin

Detroit, Michigan

Charles L. Wilkins

Fayetteville, Arkansas

Publisher's Note: Please see CD for color figures.

The Editors

Charles I. Wilkins is currently a Distinguished Professor in the Department of Chemistry and Biochemistry at the University of Arkansas (Fayetteville). His interests include mass spectrometry of polymer and copolymer materials, Fourier transform mass spectrometry, and the development of new methods to improve the utility of analytical mass spectrometry. Past research has dealt with applications of laboratory computers in chemistry, graph theoretic analysis of chemical problems, and research in chemometrics. Investigations of hyphenated analytical systems such as gas chromatography–infrared mass spectrometry and HPLC-NMR have also been of interest. He is the author of more than 235 scientific papers and 21 book chapters, in addition to editing eight books on a variety of chemistry topics.

He has received a number of honors recognizing his research contributions. Among them are the Tolman Medal of the Southern California American Chemical Society, the New York Section of the Society for Applied Spectroscopy Gold Medal, the American Chemical Society Franklin and Field Award for Outstanding Achievement in Mass Spectrometry, the Eastern Analytical Symposium Award for Outstanding Achievements in the Field of Analytical Chemistry, the Pittsburgh Analytical Award, and the University of Oregon Alumni Award for Outstanding Achievement in Pure Chemistry. He is a Fellow of the American Association for the Advancement of Science, a Fellow of the Society for Applied Spectroscopy, and a Fellow of the American Chemical Society. He is a lifetime Honorary Member of the Society of Applied Spectroscopy.

Professor Wilkins has served the chemistry profession through membership on numerous editorial advisory boards, including those of *Analytical Chemistry*, the *Journal of the American Society for Mass Spectrometry*, *Applied Spectroscopy Reviews*, and *Mass Spectrometry Reviews*, among others. He currently serves as a contributing editor for *Trends in Analytical Chemistry*, a position that he has held for almost 20 years.

Sarah Trimpin is an assistant professor at Wayne State University with interest in improving and applying mass spectrometry to difficult problems involving both complexity and insolubility. She obtained the PhD equivalent from the Max-Planck-Institute for Polymer Research, Mainz, Germany, where she pioneered the development of the solvent-free matrix-assisted laser desorption (MALDI) method demonstrating its potential with insoluble materials. After completing a postdoctoral joint position between Oregon State University, Corvallis, and the Oregon Health & Science University, Portland, Oregon, she joined David Clemmer's laboratory at Indiana University, Bloomington, IN, as a senior research associate to study ion mobility spectroscopy–mass spectrometry (IMS-MS) instrumentation and methods. Combining solvent-free MALDI and IMS-MS has led to a total solvent-free analysis approach to analyze solubility-restricted materials. She recently discovered a new ionization method she named laserspray ionization, which combines the attributes

of MALDI and electrospray ionization. The long-term goals of her research are to develop methods and instrumentation for the structural characterization and imaging of the soluble *and* insoluble components in single cells.

Dr. Trimpin has over 40 publications, including four book chapters, four reviews, and one perspective article, and has given numerous invited lectures at national and international meetings. She has received a number of honors including the German Society for Mass Spectrometry Wolfgang-Paul-Studienpreis and the Wolfgang-Paul-Promotionspreis. She was highlighted as one of *Genome Technology* magazine's Rising PIs and recently received the NSF CAREER award, the American Society for Mass Spectrometry Research Award, and the DuPont Company Young Investigator Award.

Contributors

Peter B. Armentrout

Department of Chemistry
University of Utah
Salt Lake City, Utah

Perdita E. Barran

School of Chemistry
University of Edinburgh
Edinburgh, United Kingdom

Gökhan Baykut

Bruker Daltonik GmbH
Bremen, Germany

Michael T. Bowers

Department of Chemistry and
Biochemistry
University of California Santa Barbara
Santa Barbara, California

Richard M. Caprioli

Mass Spectrometry Research Center
Departments of Chemistry and
Biochemistry
Vanderbilt University School of Medicine
Nashville, Tennessee

Emmanuelle Claude

Waters Corporation
Manchester, United Kingdom

David E. Clemmer

Department of Chemistry
Indiana University
Bloomington, Indiana

Claudia Cozma

Laboratory of Analytical Chemistry
and Biopolymer Structure Analysis
Department of Chemistry
University of Konstanz
Konstanz, Germany

Juan Fernandez de la Mora

Mechanical Engineering Department
Yale University
New Haven, Connecticut

Michael Desor

Waters Corporation-MS Technologies
Centre
Manchester, United Kingdom
and
Waters GmbH
Eschborn, Germany

Peter A. Faull

LGC Ltd.
Teddington
Middlesex, United Kingdom

Facundo M. Fernández

School of Chemistry and Biochemistry
Georgia Institute of Technology
Atlanta, Georgia

Jochen Franzen

Bruker Daltonik GmbH
Bremen, Germany

Jennifer Gidden

Arkansas Statewide Mass Spectrometry
Facility
University of Arkansas
Fayetteville, Arkansas

Kevin Giles

University of the Sciences in
Philadelphia
Philadelphia, Pennsylvania

Martin Green

Waters Corporation
Manchester, United Kingdom

Glenn A. Harris

School of Chemistry and Biochemistry
Georgia Institute of Technology
Atlanta, Georgia

Herbert H. Hill, Jr.

Department of Chemistry
Washington State University
Pullman, Washington

Ellen D. Inutan

Department of Chemistry
Wayne State University
Detroit, Michigan

Marius-Ionuț Iurașcu

Laboratory of Analytical Chemistry
and Biopolymer Structure Analysis
Department of Chemistry
University of Konstanz
Konstanz, Germany

Shelley N. Jackson

NIDA IRP, NIH
Baltimore, Maryland

Kimberly Kaplan

Department of Chemistry
Washington State University
Pullman, Washington

Mark Kwasnik

School of Chemistry and Biochemistry
Georgia Institute of Technology
Atlanta, Georgia

James Langridge

Waters Corporation-MS Technologies
Centre
Manchester, United Kingdom
and
Waters GmbH
Eschborn, Germany

Barbara S. Larsen

DuPont Corporate Center for Analytical
Sciences
Wilmington, Delaware

Hilary Major

Waters Corporation
Manchester, United Kingdom

Jody C. May

Laboratory for Biological Mass
Spectrometry
Department of Chemistry
Texas A&M University
College Station, Texas

Bryan J. McCullough

LGC Ltd.
Teddington
Middlesex, United Kingdom

Charles N. McEwen

University of the Sciences in
Philadelphia
Philadelphia, Pennsylvania

John A. McLean

Department of Chemistry
Vanderbilt Institute of Chemical
Biology
Vanderbilt Institute for Integrative
Biosystems Research and Education
Vanderbilt University
Nashville, Tennessee

Jasna Peter-Katalinić

Institute for Medical Physics and
Biophysics
Westfalian Wilhelms University
Muenster
Muenster, Germany
and
Department of Biotechnology
University of Rijeka
Rijeka, Croatia

Michael Przybylski

Laboratory of Analytical Chemistry
and Biopolymer Structure Analysis
Department of Chemistry
University of Konstanz
Konstanz, Germany

Oliver Raether

Bruker Daltonik GmbH
Bremen, Germany

Whitney B. Ridenour

Mass Spectrometry Research Center
Departments of Chemistry and
Biochemistry
Vanderbilt University School of
Medicine
Nashville, Tennessee

David H. Russell

Laboratory for Biological Mass
Spectrometry
Department of Chemistry
Texas A&M University
College Station, Texas

J. Albert Schultz

Ionwerks Inc.
Houston, Texas

Nick Tomczyk

Waters Corporation-MS Technologies
Centre
Manchester, United Kingdom
and
Waters GmbH
Eschborn, Germany

Sarah Trimpin

Department of Chemistry
Wayne State University
Detroit, Michigan

Sergey Y. Vakhrushev

Copenhagen Center for Glycomics
Department of Cellular and Molecular
Medicine
Panum Institute
University of Copenhagen
Copenhagen, Denmark

Oliver von Halem

Bruker Daltonik GmbH
Bremen, Germany

Amina S. Woods

NIDA IRP, NIH
Baltimore, Maryland

Thomas Wyttenbach

Department of Chemistry and
Biochemistry
University of California Santa Barbara
Santa Barbara, California

Contents

Preface.....	ix
The Editors.....	xi
Contributors	xiii

Fundamentals

Chapter 1	Developments in Ion Mobility: Theory, Instrumentation, and Applications.....	3
	<i>Thomas Wytenbach, Jennifer Gidden, and Michael T. Bowers</i>	
Chapter 2	Electronic State Chromatography: Ion Mobility of Atomic Cations and Their Electronic States.....	31
	<i>Peter B. Armentrout</i>	
Chapter 3	Measuring Ion Mobility in a Gas Jet Formed by Adiabatic Expansion.....	53
	<i>Gökhan Baykut, Oliver von Halem, Jochen Franzen, and Oliver Raether</i>	

Instrumentation

Chapter 4	Development of an Ion-Mobility-Capable Quadrupole Time-of-Flight Mass Spectrometer to Examine Protein Conformation in the Gas Phase	75
	<i>Bryan J. McCullough, Peter A. Faull, and Perdita E. Barran</i>	
Chapter 5	The Differential Mobility Analyzer (DMA): Adding a True Mobility Dimension to a Preexisting API-MS.....	105
	<i>Juan Fernandez de la Mora</i>	
Chapter 6	A Cryogenic-Temperature Ion Mobility Mass Spectrometer for Improved Ion Mobility Resolution.....	137
	<i>Jody C. May and David H. Russell</i>	

Chapter 7	Multiplexed Ion Mobility Spectrometry and Ion Mobility–Mass Spectrometry	153
	<i>Glenn A. Harris, Mark Kwasnik, and Facundo M. Fernández</i>	
Chapter 8	IMS/MS Applied to Direct Ionization Using the Atmospheric Solids Analysis Probe Method	171
	<i>Charles N. McEwen, Hilary Major, Martin Green, Kevin Giles, and Sarah Trimpin</i>	
Chapter 9	Total Solvent-Free Analysis, Charge Remote Fragmentation, and Structures of Highly Charged Laserspray Ions Using IMS-MS	189
	<i>Ellen D. Inutan, Emmanuelle Claude, and Sarah Trimpin</i>	
 Applications		
Chapter 10	Snapshot, Conformation, and Bulk Fragmentation: Characterization of Polymeric Architectures Using ESI-IMS-MS	215
	<i>Sarah Trimpin, David E. Clemmer, and Barbara S. Larsen</i>	
Chapter 11	Metabolomics by Ion Mobility–Mass Spectrometry	237
	<i>Kimberly Kaplan and Herbert H. Hill, Jr.</i>	
Chapter 12	Ion Mobility MALDI Mass Spectrometry and Its Applications	257
	<i>Amina S. Woods, J. Albert Schultz, and Shelley N. Jackson</i>	
Chapter 13	Profiling and Imaging of Tissues by Imaging Ion Mobility–Mass Spectrometry	269
	<i>Whitney B. Parson and Richard M. Caprioli</i>	
Chapter 14	Deciphering Carbohydrate Structures by IMS-MS: Applications to Biological Features Related to Carbohydrate Chemistry and Biology	287
	<i>Sergey Y. Vakhrushev and Jasna Peter-Katalinić</i>	

Chapter 15 Structural Characterization of Oligomer-Aggregates of β -Amyloid Polypeptide Using Ion Mobility Mass Spectrometry 313
Marius-Ionuț Iurașcu, Claudia Cozma, James Langridge, Nick Tomczyk, Michael Desor, and Michael Przybylski

Chapter 16 The Conformational Landscape of Biomolecules in Ion Mobility–Mass Spectrometry 327
Jody C. May and John A. McLean

Index 345

1 Developments in Ion Mobility

Theory, Instrumentation, and Applications

Fundamentals

Thomas Wytenbach, former Editor
and Michael C. Bowles

CONTENTS

1. Introduction to Ion Mobility Spectrometry	1
2. Theoretical Foundations of Ion Mobility	2
3. Experimental Techniques in Ion Mobility Spectrometry	3
4. Applications of Ion Mobility Spectrometry	4
5. Theoretical Foundations of Ion Mobility Spectrometry	5
6. Experimental Techniques in Ion Mobility Spectrometry	6
7. Applications of Ion Mobility Spectrometry	7
8. Theoretical Foundations of Ion Mobility Spectrometry	8
9. Experimental Techniques in Ion Mobility Spectrometry	9
10. Applications of Ion Mobility Spectrometry	10
11. Theoretical Foundations of Ion Mobility Spectrometry	11
12. Experimental Techniques in Ion Mobility Spectrometry	12
13. Applications of Ion Mobility Spectrometry	13
14. Theoretical Foundations of Ion Mobility Spectrometry	14
15. Experimental Techniques in Ion Mobility Spectrometry	15
16. Applications of Ion Mobility Spectrometry	16
17. Theoretical Foundations of Ion Mobility Spectrometry	17
18. Experimental Techniques in Ion Mobility Spectrometry	18
19. Applications of Ion Mobility Spectrometry	19
20. Theoretical Foundations of Ion Mobility Spectrometry	20
21. Experimental Techniques in Ion Mobility Spectrometry	21
22. Applications of Ion Mobility Spectrometry	22
23. Theoretical Foundations of Ion Mobility Spectrometry	23
24. Experimental Techniques in Ion Mobility Spectrometry	24
25. Applications of Ion Mobility Spectrometry	25
26. Theoretical Foundations of Ion Mobility Spectrometry	26
27. Experimental Techniques in Ion Mobility Spectrometry	27
28. Applications of Ion Mobility Spectrometry	28
29. Theoretical Foundations of Ion Mobility Spectrometry	29
30. Experimental Techniques in Ion Mobility Spectrometry	30
31. Applications of Ion Mobility Spectrometry	31
32. Theoretical Foundations of Ion Mobility Spectrometry	32
33. Experimental Techniques in Ion Mobility Spectrometry	33
34. Applications of Ion Mobility Spectrometry	34
35. Theoretical Foundations of Ion Mobility Spectrometry	35
36. Experimental Techniques in Ion Mobility Spectrometry	36
37. Applications of Ion Mobility Spectrometry	37
38. Theoretical Foundations of Ion Mobility Spectrometry	38
39. Experimental Techniques in Ion Mobility Spectrometry	39
40. Applications of Ion Mobility Spectrometry	40
41. Theoretical Foundations of Ion Mobility Spectrometry	41
42. Experimental Techniques in Ion Mobility Spectrometry	42
43. Applications of Ion Mobility Spectrometry	43
44. Theoretical Foundations of Ion Mobility Spectrometry	44
45. Experimental Techniques in Ion Mobility Spectrometry	45
46. Applications of Ion Mobility Spectrometry	46
47. Theoretical Foundations of Ion Mobility Spectrometry	47
48. Experimental Techniques in Ion Mobility Spectrometry	48
49. Applications of Ion Mobility Spectrometry	49
50. Theoretical Foundations of Ion Mobility Spectrometry	50
51. Experimental Techniques in Ion Mobility Spectrometry	51
52. Applications of Ion Mobility Spectrometry	52
53. Theoretical Foundations of Ion Mobility Spectrometry	53
54. Experimental Techniques in Ion Mobility Spectrometry	54
55. Applications of Ion Mobility Spectrometry	55
56. Theoretical Foundations of Ion Mobility Spectrometry	56
57. Experimental Techniques in Ion Mobility Spectrometry	57
58. Applications of Ion Mobility Spectrometry	58
59. Theoretical Foundations of Ion Mobility Spectrometry	59
60. Experimental Techniques in Ion Mobility Spectrometry	60
61. Applications of Ion Mobility Spectrometry	61
62. Theoretical Foundations of Ion Mobility Spectrometry	62
63. Experimental Techniques in Ion Mobility Spectrometry	63
64. Applications of Ion Mobility Spectrometry	64
65. Theoretical Foundations of Ion Mobility Spectrometry	65
66. Experimental Techniques in Ion Mobility Spectrometry	66
67. Applications of Ion Mobility Spectrometry	67
68. Theoretical Foundations of Ion Mobility Spectrometry	68
69. Experimental Techniques in Ion Mobility Spectrometry	69
70. Applications of Ion Mobility Spectrometry	70
71. Theoretical Foundations of Ion Mobility Spectrometry	71
72. Experimental Techniques in Ion Mobility Spectrometry	72
73. Applications of Ion Mobility Spectrometry	73
74. Theoretical Foundations of Ion Mobility Spectrometry	74
75. Experimental Techniques in Ion Mobility Spectrometry	75
76. Applications of Ion Mobility Spectrometry	76
77. Theoretical Foundations of Ion Mobility Spectrometry	77
78. Experimental Techniques in Ion Mobility Spectrometry	78
79. Applications of Ion Mobility Spectrometry	79
80. Theoretical Foundations of Ion Mobility Spectrometry	80
81. Experimental Techniques in Ion Mobility Spectrometry	81
82. Applications of Ion Mobility Spectrometry	82
83. Theoretical Foundations of Ion Mobility Spectrometry	83
84. Experimental Techniques in Ion Mobility Spectrometry	84
85. Applications of Ion Mobility Spectrometry	85
86. Theoretical Foundations of Ion Mobility Spectrometry	86
87. Experimental Techniques in Ion Mobility Spectrometry	87
88. Applications of Ion Mobility Spectrometry	88
89. Theoretical Foundations of Ion Mobility Spectrometry	89
90. Experimental Techniques in Ion Mobility Spectrometry	90
91. Applications of Ion Mobility Spectrometry	91
92. Theoretical Foundations of Ion Mobility Spectrometry	92
93. Experimental Techniques in Ion Mobility Spectrometry	93
94. Applications of Ion Mobility Spectrometry	94
95. Theoretical Foundations of Ion Mobility Spectrometry	95
96. Experimental Techniques in Ion Mobility Spectrometry	96
97. Applications of Ion Mobility Spectrometry	97
98. Theoretical Foundations of Ion Mobility Spectrometry	98
99. Experimental Techniques in Ion Mobility Spectrometry	99
100. Applications of Ion Mobility Spectrometry	100

INTRODUCTION

The field of ion mobility spectrometry (IMS) has grown rapidly in the past few years, and it is now one of the most active areas of research in analytical chemistry. This book provides a comprehensive overview of the field, covering the basic principles of ion mobility, the various types of IMS instruments, and the many applications of this technology. The book is written for both students and researchers, and it includes numerous examples and references to help the reader understand the field and its potential.

Fundamentals

1 Developments in Ion Mobility *Theory, Instrumentation, and Applications*

*Thomas Wyttenbach, Jennifer Gidden,
and Michael T. Bowers*

CONTENTS

1.1	Introduction	3
1.2	Theory.....	4
1.2.1	Ion Mobility	4
1.2.2	Collision Cross Section.....	5
1.2.3	Resolution	7
1.2.4	Reactive and Dynamic Ions.....	8
1.2.5	Reactive Buffer Gases	9
1.3	Instrumentation.....	10
1.3.1	Ion Source	10
1.3.2	IMS Entrance Section.....	11
1.3.3	IMS Drift Tube	12
1.3.4	IMS Exit Section	13
1.3.5	Alternatives to IMS Drift Tubes	14
1.3.6	Mass Spectrometers.....	15
1.4	Applications.....	16
1.4.1	Peptides, Proteins, and Aggregation Mechanisms	16
1.4.2	Structure and Energetics of Dinucleotides	20
1.4.3	Hydration of Biomolecules	24
	Acknowledgments.....	27
	References.....	27

1.1 INTRODUCTION

In this chapter we focus on ion mobility spectrometry (IMS) employed to obtain structural information of polyatomic ions. In these applications—reviewed by Clemmer and Jarrold,⁽¹⁾ Wyttenbach and Bowers,⁽²⁾ Creaser et al.,⁽³⁾ Weis,⁽⁴⁾ and

Bohrer et al.⁽⁵⁾—IMS always occurs in combination with mass spectrometry (MS). We divide the chapter into three sections covering theory, instrumental aspects, and research applications from our lab. In the theoretical section we cover some of the basic theory of IMS, how ions exposed to an electric field move in a buffer gas, and how this motion relates to the structure of the ion. In the instrumentation section we present basic hybrid IMS-MS setups and their components and discuss issues to consider in the design of such an instrument. And finally, in the applications section we present a few instructive application examples from our lab to illustrate the concepts outlined in the theory and instrument sections and to demonstrate the potential of the method to solve biochemically relevant problems.

1.2 THEORY

1.2.1 ION MOBILITY

Ions exposed to an electric field experience a force and are accelerated along the field lines. Upon addition of a buffer gas, the motion of the ions becomes more complicated as collisions with the gas scatter the ions in random directions as it diffuses. However, if an ion cloud is given enough time to reach equilibrium and the electric field is uniform throughout, the ion cloud will travel with constant velocity parallel to the field lines and simultaneously grow in size due to diffusion. This constant equilibrium velocity is the result of forward acceleration by the field and decelerating friction by collisions. Following Mason and McDaniel,⁽⁶⁾ for weak electric fields of magnitude E , the drift velocity v is directly proportional to E with the proportional-ity constant K called ion mobility

$$v = K E \quad (1.1)$$

Since v is inversely proportional to the buffer gas number density N , the mobility K is also inversely proportional to N . Here N (in units of molecules per volume) is used as the relevant quantity to express pressure because N is, in contrast to pressure p , decoupled from the temperature T . Because K depends on N it is practical to convert K into the pressure-independent quantity $K_0 \propto NK$, where K_0 is termed the reduced mobility

$$K_0 = \frac{p}{p_0} \frac{T_0}{T} K \quad (1.2)$$

with the constants $p_0 = 760$ Torr and $T_0 = 273.15$ K.

A field is considered weak if the average ion energy acquired from the field is small compared to the thermal energy of the buffer gas molecules. This ion field energy is proportional to v^2 or $(KE)^2$. However, for a given ion with given $K_0 \propto NK$ it is the ratio E/N which determines whether a field is weak or strong, and collisional heating due to the field is given by Equation (1.3):

$$T_{\text{eff}} - T = (M/3k_B) (NK)^2 (E/N)^2 \quad (1.3)$$