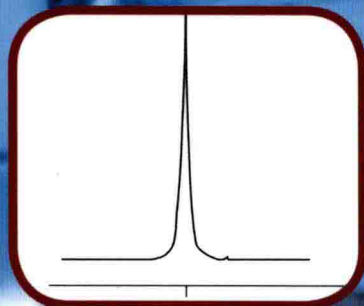
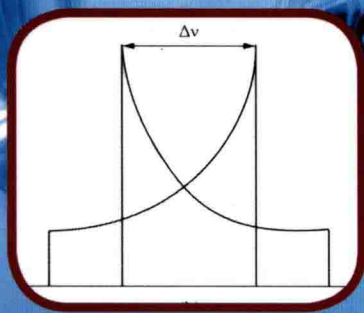


NMR SPECTROSCOPY IN LIQUIDS AND SOLIDS



NMR SPECTROSCOPY IN LIQUIDS AND SOLIDS

常州大学图书馆
VLA. 藏 中 书 章
VLADIMIR. BAKHMUTOV



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

© 2015 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper
Version Date: 20141118

International Standard Book Number-13: 978-1-4822-6270-4 (Paperback)

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

Bakhmutov, Vladimir I.
NMR spectroscopy in liquids and solids / Vladimir I. Bakhmutov.
pages cm
"A CRC title."
Includes bibliographical references and index.
ISBN 978-1-4822-6270-4 (alk. paper)
1. Nuclear magnetic resonance spectroscopy. 2. Spectrum analysis. I. Title. II. Title:
Nuclear magnetic resonance spectroscopy in liquids and solids.

QD96.N8B35 2014
543'.66--dc23

2014043706

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

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

Preface

This book is intended for those who are just beginning research activity in chemistry, biochemistry, geochemistry, chemical engineering, or other science and wish to use NMR as the main research method for investigating solutions and the solid state. This text is not a reference book with a great number of tables and NMR data that can be found elsewhere in the literature; however, it does cover basic NMR concepts that must be understood to perform NMR experiments on liquid and solid samples and to interpret the data collected to determine structures and molecular dynamics. The book has been written by an expert who began his research career using iron permanent electromagnets and continuous-wave irradiation, later moving on to superconducting electromagnets with pulsing NMR. Many NMR experiments mentioned in this text have been taken from the author's own experience, including studies of inorganic and organic molecules in solutions and molecular aggregates and materials in the solid state.

What is new and different in this book?

1. Presents current understanding and applications of solution and solid-state NMR techniques
2. Combines and formulates common principles for NMR experiments in gases, liquids, and solids
3. Pays considerable attention to nuclear relaxation, from the phenomenon itself to applications in solutions and solids
4. Formulates general strategies for studies and demonstrates how to choose the appropriate experiment, what methods and pulse sequences are suitable for particular situations, and how to assign signals in the NMR spectra of simple and complex molecular systems

The book is organized into ten chapters that include numerous illustrations and recommended literature. Chapters 1 to 4 cover the basic principles, and Chapters 5 to 10 describe NMR applications. These chapters have been written in such a way that they can be presented as ten lectures for NMR spectroscopy courses aimed at undergraduate and postgraduate students or young researchers at colleges and universities. Only minimal knowledge of physics and quantum mechanics is assumed.

Introduction

Nuclear magnetic resonance (NMR) is a powerful instrumental method that rapidly and adequately handles a large number of scientific and applied tasks on both the molecular and atomic levels. Because a NMR signal can be detected in gases, solutions, liquids, and solids, including crystals and amorphous homogeneous or heterogeneous systems, this method can be successfully applied in physics, chemistry, food chemistry, biochemistry, geochemistry, biology, geology, archeology, pharmaceuticals, and materials science fields. Moreover, an interesting version of NMR, magnetic resonance imaging (MRI), has become a reliable diagnostic tool in both human and veterinary science and medicine, particularly for research into the brain. MRI is also applicable to the study of materials chemistry.

The modern arsenal of NMR methods and techniques is extremely large. Due to the increasing complexity of objects involved in NMR studies, this arsenal is constantly growing and being modified. Over its 70-year history, NMR research has stimulated the development of new scientific fields. Successes in radiofrequency technology from 1952 to 1953 led to the appearance of the first commercial NMR spectrometers, which strongly impacted research in chemistry, biochemistry, and biology. In turn, the synthesis and study of complex objects, such as biochemical molecular systems and complex inorganic/organic molecular aggregates, required the availability of more powerful NMR instrumentation offering better spectral resolution and sensitivity. Such improvements would have been impossible in the absence of innovations in magnet technology that created stronger and stronger homogeneous magnetic fields. In addition, the development of computers capable of very fast Fourier transform (FFT) processing has resulted in the routine use of two-, three-, or four-dimensional NMR spectroscopy for structural analyses in solutions and solids to assign signals in the NMR spectra of complex molecular systems.

Due to the impressive development of NMR techniques, NMR applications are expanding from molecular and low-temperature physics to archeology, where, for example, the natural destruction of wood is the focus of researchers. In spite of such developments, it is obvious that without a deep understanding of NMR and nuclear relaxation their successful application cannot be guaranteed. Moreover, such an understanding cannot be gained by any computer search (such as Google, for example), a popular approach among students and young researchers. Searches such as these can provide only fragmented knowledge.

With regard to the history of NMR,¹ after the first successful observation of NMR signals in gases occurred in 1937, C.J. Gorter attempted to detect resonances in the condensed phase in order to detect lithium nuclei in crystalline LiF and protons in crystalline potassium alum. Similar experiments had been performed on ¹⁹F nuclei in the crystal solid KF but no NMR signals were found. Today, it is known that the nuclei were invisible due to the exclusively long relaxation times in the very

pure crystals. Relaxation times are still an issue for NMR beginners, as the behavior of nuclei in NMR experiments is time dependent, and their relaxation times strongly affect the NMR data obtained.

In contrast, due to the relatively short relaxation times of protons in paraffin wax and water, researchers Purcell and Bloch reported the first NMR signals in the condensed phase in 1945. These experiments led to the application of NMR as an analytical method. Later, Blombergen, Purcell, and Pound² formulated the theory of nuclear relaxation now referred to as the BPP theory. It should be noted that the BPP theory is valid for all states of matter—solids, liquids, or gases—where the dipole–dipole internuclear interactions govern nuclear relaxation via molecular motions. Extremely low-temperature relaxation measurements performed in solid H₂ at a temperature of 1 K have emphasized the importance of such motions in the dipole–dipole relaxation process. It should be noted that further reconsiderations of nuclear relaxation processes have led to only small additions to the relaxation theory first published in 1948.

The rate and the character of molecular motions strongly change upon going from liquids to solids. This factor affects the experimental conditions required for the detection of NMR signals. Ice demonstrates the principal differences in NMR experiments on liquids and solids. The line width of the ¹H resonance in liquid water is very small (<1 Hz), whereas the resonance of solid water broadens up to ~10⁵ Hz due to strong dipolar proton–proton coupling against a background of very slow molecular motions. It is obvious that different technical solutions are needed to detect NMR signals in solids.

Despite the first early successes in understanding the relaxation behavior of nuclei in liquids and solids, the relaxation mechanism in crystal solids, such as CaF₂, remained unclear. In 1949, Bloembergen³ reported on the nature of ¹⁹F relaxation, termed *spin diffusion*. This relaxation occurs via energy diffusion from nuclear spins to paramagnetic centers present in the crystal as impurities, and it can be effective for the strong dipolar coupling ¹⁹F–¹⁹F.

The early classical work mentioned above and the later discovery of chemical shifts and spin–spin coupling illustrate important features of NMR: The NMR spectra recorded in liquids and solids show a number of distinguished nuclei in structurally different molecules and/or groups and even their mutual dispositions, whereas nuclear relaxation opens the way to describing molecular dynamics ranging from isotropic or anisotropic reorientations in liquids to phase transitions in rigid solids. These unique features make NMR a powerful analytical method.

The diverse NMR experiments on liquids or solids can be represented by the general scheme shown in Figure I.1. Here, each step, from the preparation of samples to interpretations and conclusions, is equally important. Actions taken at each step can result in errors, experimental or interpretational, because modern NMR spectrometers are complex multiple-pulse devices that operate with low or very high magnetic fields, up to 21.14 T. The modern tendency is to aim for full automation in the performance of experiments, including sample changes and even interpretation of the spectra. It should be noted that such automation exemplifies a black-box approach that can be successful for the routine analysis of reaction mixtures or large series of similar compounds. However, such an approach is quite ineffective in a research laboratory, where precise determination of new structures is an important part of studies. In

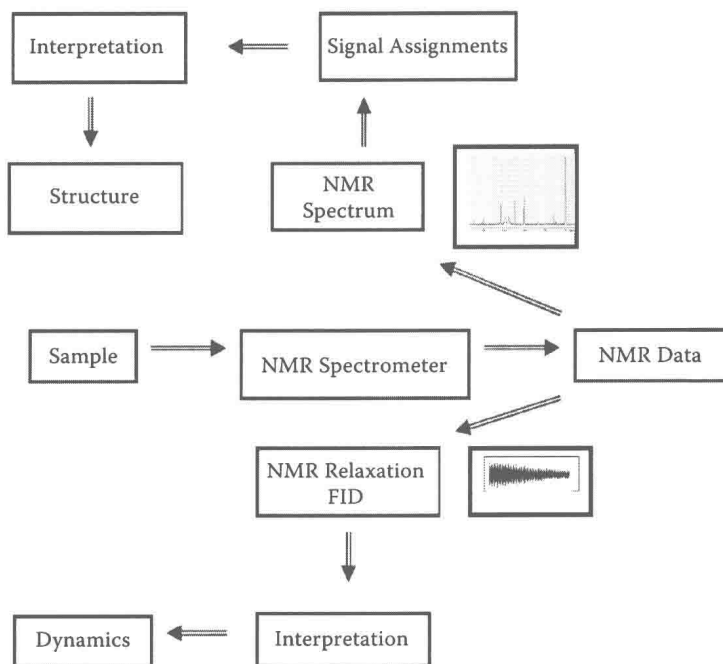


FIGURE I.1 General scheme of NMR experiments performed on solutions and solids to probe their structure and dynamics.

addition, artifact phenomena can appear in NMR experiments, further complicating their interpretation. Their recognition again requires at least minimal understanding of the physical aspects of NMR. Finally, it should be emphasized that NMR experiments resulting in NMR spectra or time-dependent data are revealing only the behavior of nuclear spins and their ensembles in the magnetic field, not groups of atoms and molecules or more complex aggregates. Understanding their nature is a product of our interpretations based on experience and numerous spectral structural relationships.

This book is compressed to ten chapters to minimize its volume. The first three chapters consider the theoretical basis of NMR spectroscopy, the theory of NMR relaxation, and the practice of relaxation measurements. Chapter 4 discusses the general aspects of molecular dynamics and their relationships with NMR. NMR spectroscopy and relaxation studies in solutions are addressed in Chapters 5 and 6, and Chapter 7 considers special issues of NMR in solutions. Chapter 8 leads into the solid-state portion of the book by introducing the general principles and strategies involved in solid-state NMR studies and provides examples of applications of relaxation for the determination of molecular dynamics in diamagnetic solids. Chapter 10 concludes with a discussion on special issues of solid-state NMR, including NMR and NMR relaxation in paramagnetic solids, an area requiring additional knowledge. Finally, the chapters are accompanied by references and recommended literature for further reading.

The book is addressed to undergraduate students, NMR beginners, and young scientists who are planning to work or are already working in the various fields of chemistry, biochemistry, biology, pharmaceutical sciences, and materials science. It provides an introduction to the general concepts of NMR and the principles of its applications, including how to perform adequate NMR experiments and how to interpret the NMR data collected in liquids and solids to characterize molecule systems in terms of their structure and dynamics.

REFERENCES

1. Andrew, E.R. and Szczesniak, E. (1995). *Prog. Nucl. Magn. Reson. Spectr.*, 28: 11.
2. Blombergen, N., Purcell, E.M., and Pound, R.V. (1948). *Phys. Rev.*, 73: 679.
3. Bloembergen, N. (1949). *Physica*, 15: 386.

Author

Vladimir I. Bakhmutov, PhD, works in the Department of Chemistry at Texas A&M University. The 330 scientific articles and 5 books that he has written and published document his outstanding contributions to chemical physics research. Dr. Bakhmutov's research interests include extensive applications of solution and solid-state NMR techniques for chemistry, molecular physics, and materials science. NMR relaxation in liquids and solids applied for structural and dynamic studies is also an area of interest. Dr. Bakhmutov has been granted visiting professorships by Zurich University, Switzerland; Bourgogne University, Dijon, France; Rennes University, France; CINVESTAV, Mexico; and Iberdrola, Zaragoza, Spain.

Contents

Preface.....	ix
Introduction.....	xi
Author	xv

Chapter 1	Physical Basis of Nuclear Magnetic Resonance.....	1
1.1	Nuclei in the External Magnetic Field.....	2
1.2	Radiofrequency Irradiation: Continuous-Wave and Radiofrequency Pulses	7
1.3	From Nuclear Relaxation to Shapes of NMR Signals.....	11
1.4	Registration of NMR Signals: General Principles and NMR Equipment	14
1.4.1	Magnets, Decouplers, and NMR Probes.....	16
1.4.2	Dead Time in NMR Experiments: Influence on NMR Data	18
1.4.3	Spectral Resolution.....	19
1.5	Enhancement of Sensitivity in NMR Experiments	20
1.6	Two-Dimensional and Multi-Quantum NMR Experiments: General Aspects.....	21
1.6.1	Artifacts in 2D NMR	24
1.6.2	Multi-Quantum NMR	24
	References and Recommended Literature.....	26

Chapter 2	Chemical Shifts and Nuclear Coupling: Theory and Practical Consequences.....	27
2.1	Phenomenology of Chemical Shift.....	27
2.1.1	Chemical Shift in Diamagnetic Molecular Systems....	30
2.1.2	Relationship Chemical Shift and Atomic Charge	32
2.1.3	Predicting Chemical Shift Values.	34
2.1.4	Isotropic Chemical Shift	35
2.2	Chemical Shifts in the Presence of Unpaired Electrons	37
2.2.1	Knight Shifts	38
2.3	Spin–Spin Coupling	39
2.3.1	Strongly Coupled Spin Systems	40
2.3.2	Spin–Spin Coupling via Chemical Bonds.....	43
2.3.3	Spin–Spin Coupling through Space	46
2.3.4	Proton–Proton Exchange Coupling.....	46
2.4	Dipolar Coupling.....	48
2.5	Quadrupolar Coupling.....	49
	References and Recommended Literature.....	51

Chapter 3	Nuclear Relaxation: Theory and Measurements	53
3.1	Molecular Motions: Common Characteristics	53
3.1.1	Isotropic and Anisotropic Molecular Reorientations	56
3.2	Mechanisms of Spin–Spin and Spin–Lattice Nuclear Relaxation	58
3.2.1	Intramolecular Dipole–Dipole Relaxation	59
3.2.2	Intermolecular Dipole–Dipole Relaxation	62
3.2.3	Quadrupolar Relaxation	63
3.2.4	Relaxation by Chemical Shift Anisotropy	64
3.2.5	Spin–Rotation and Scalar Relaxation Mechanisms	65
3.2.6	Cross-Relaxation and Coupled Relaxation	67
3.3	Spin Diffusion in Solids	68
3.4	Paramagnetic Relaxation	70
3.5	Relaxation Time Measurements	71
3.5.1	Non-Selective, Selective, and Bi-Selective T_1 Times	71
3.5.2	Measuring $T_{1\rho}$ and T_2 Times	73
3.6	Experiments and Measurements: Errors and Problems	75
3.6.1	Instrumental Errors	75
3.6.2	Treatment of Relaxation Curves: Approaches and Problems	76
3.7	Artifacts in Relaxation Time Measurements	78
	References and Recommended Literature	81
 Chapter 4	 NMR and Molecular Dynamics: General Principles	 83
4.1	Kinetics of Chemical Reactions by NMR Spectroscopy	85
4.2	Chemical Exchange	86
4.2.1	Line-Shape Analysis	87
4.2.2	Slow Chemical Exchange	90
4.2.3	Exchange NMR Spectroscopy	92
4.2.4	Carr–Purcell–Meiboom–Gill Relaxation Dispersion	93
4.3	Molecular Mobility from Relaxation Times	95
4.3.1	Dipole–Dipole Relaxation, Nuclear Overhauser Effect, and Molecular Mobility	97
4.3.2	Effects of Molecular Motional Anisotropy on Nuclear Relaxation	99
4.3.3	Molecular Dynamics in the Presence of Correlation Time Distributions	104
4.3.4	Distribution of Activation Energies	107
4.4	NMR Relaxometry: Diffusion Coefficients	108
4.5	Molecular Dynamics from Low-Field NMR	110
	References and Recommended Literature	110

Chapter 5	NMR Spectroscopy in Solutions: Practice and Strategies of Structural Studies.....	113
5.1	Preparation of NMR Samples: Minimal Requirements.....	113
5.1.1	Adjustment of Spectral Resolution and Spectral Manipulations.....	114
5.1.2	Reference Lines.....	115
5.2	Structural Studies by Solution NMR: General Strategies and 1D and 2D NMR Experiments	116
5.2.1	From 1D NMR to 2D Correlation Spectroscopy	116
5.2.2	Multi-Quantum NMR	119
5.2.3	Examples of Structural Studies	121
5.2.4	Ultrafast NMR	128
5.3	Conformational (Isomeric) Analysis by NMR in Solutions.....	129
5.3.1	Common Principles.....	129
5.3.2	Determination of Molecular Geometry (Conformations, Isomers) via Chemical Shifts and Spin–Spin Coupling Constants through Chemical Bonds	130
5.3.3	Molecular Geometry and Spin–Spin Coupling through Space.....	136
5.3.4	Conformational Analysis in the Presence of Fast Interconversions	138
5.4	NOE and Residual Dipolar Coupling Measurements in Structural Studies.....	141
	References and Recommended Literature.....	145
Chapter 6	NMR Relaxation in Solutions: Applications.....	147
6.1	Partially Relaxed NMR Spectra: Resolving the Unresolved Signals and Assigning NMR Signals.....	147
6.2	Relaxation Times in Solutions: Quadrupolar Coupling Constants and Chemical Shift Anisotropy	149
6.2.1	QCC Values from Variable-Temperature Relaxation Experiments and T_{1min} Times	151
6.2.2	T_1 Relaxation and DQCC Values in Mobile Structural Units.....	156
6.2.3	Chemical-Shift Anisotropy Values from T_1 Data.....	159
6.3	NMR Relaxation and Intermolecular Interactions	160
6.3.1	Weak Bonding.....	160
6.3.2	Ion Pairing.....	162
6.3.3	Complexation.....	164
6.4	Solvent Relaxation	165
6.5	Relaxation in Molecular Systems with Chemical Exchanges	167

6.6	Structural Aspects Obtained from Relaxation in Solutions	170
6.6.1	^1H T_1 Criterion in Structural Assignments	170
6.6.2	Interatomic Distances from T_1 Data in Solutions	173
	References and Recommended Literature.....	178
Chapter 7	Special Issues in Solution NMR	181
7.1	Optical Isomers in NMR Spectra	181
7.2	Solution NMR of Biomolecules: General Principles.....	184
7.3	Dynamics of Liquids by NMR	190
7.3.1	Diffusion NMR Spectroscopy in Liquids	191
7.3.2	High-Pressure NMR: Structure and Dynamics of Liquids	194
7.4	<i>para</i> -Hydrogen and NMR Spectroscopy in Solutions.....	197
7.5	Solution NMR Spectroscopy and Heterogeneous Molecular Systems.....	199
7.5.1	Low-Field NMR in Heterogeneous Samples.....	201
7.6	Free Radicals in NMR Spectra of Solutions	205
	References and Recommended Literature.....	210
Chapter 8	Solid-State NMR Spectroscopy: General Principles and Strategies ...	213
8.1	Detection of NMR Signals in Solids	214
8.1.1	MAS NMR vs. Wide-Line NMR.....	217
8.2	General Approaches and Strategies of NMR Studies in Solids.....	220
8.2.1	Nuclei with Spins of $1/2$	220
8.2.2	NMR Experiments on Dipolar Recoupling.....	221
8.2.3	Quadrupolar Nuclei	222
8.2.3.1	Multiple Quantum NMR of Quadrupolar Nuclei in Solids	225
8.2.4	High-Pressure NMR in Disordered Solids.....	225
8.3	Enhancing Spectral Resolution in Solid-State NMR	226
8.3.1	Resolving Signals from Different Structural Units in Solids via Paramagnetic Effects.....	230
8.4	Assignments of Signals	231
8.4.1	Proton–Proton Proximity and the Assignment of Signals in Solid-State ^1H NMR Spectra	234
8.4.2	Magnetic Shielding Tensors vs. Isotropic Chemical Shifts	234
8.5	Multinuclear Solid-State NMR Applications	239
8.5.1	^{31}P Solid-State NMR	239
8.5.1.1	^{31}P Chemical Shift Tensors	241
8.5.2	^{14}N Solid-State NMR.....	243
8.5.2.1	Single-Crystal ^{14}N NMR Experiments	245

8.5.2.2	^{14}N NMR in Static Powders.....	247
8.5.2.3	^{14}N MAS NMR.....	247
8.5.3	Alkali Metal Ions Li^+ , Na^+ , K^+ , Rb^+ , and Cs^+ for Solid-State NMR.....	249
8.5.4	^{43}Ca Solid-State NMR.....	252
8.5.5	$^{35,37}\text{Cl}$, $^{78,81}\text{Br}$, ^{127}I , and ^{17}O Solid-State NMR.....	254
8.5.6	^{51}V , ^{93}Nb , and ^{181}Ta Solid-State NMR.....	256
	References and Recommended Literature.....	257

Chapter 9	Molecular Dynamics and Nuclear Relaxation in Solids: Applications.....	261
9.1	Temperature Control and Calibration in Solid-State NMR.....	262
9.2	Unusually Fast Molecular Dynamics in Solids.....	263
9.3	Molecular Dynamics in Solids Determined by Full Line-Shape Analysis.....	264
9.4	One- and Two-Dimensional Exchange NMR Spectroscopy in Solids: Slow Molecular Dynamics.....	266
9.5	Dynamics in Solids by Cross-Polarization NMR Experiments.....	268
9.6	Molecular Dynamics in Solids by NMR Relaxation Measurements: Common Aspects of Applications.....	271
9.6.1	Nuclear Relaxation in Spinning Solids.....	272
9.6.2	Methodology of Solid-State Relaxation Studies.....	274
9.6.3	General Comments on Non-Exponential Relaxation in Solids.....	277
9.7	Dynamics in Heterogeneous and Disordered Solids: NMR Spectra and Relaxation Dispersion.....	278
9.8	Dynamics in Solids under High Pressure.....	282
	References and Recommended Literature.....	284

Chapter 10	Solid-State NMR: Special Issues.....	287
10.1	Solid-State NMR of Proteins.....	287
10.1.1	Chemical Shift Tensors in Proteins.....	290
10.2	Solid-State NMR in Metals and Alloys.....	292
10.3	Porous Diamagnetic Solids: Porosity via NMR Experiments.....	295
10.3.1	NMR Cryoporometry.....	296
10.3.2	NMR Relaxometry.....	297
10.3.2.1	NMR Relaxometry for Gases.....	300
10.3.2.2	Low-Field NMR Relaxometry under High Pressure.....	301
10.4	Solid-State NMR and Paramagnetic Molecular Systems.....	303

10.4.1	Spin Echo Mapping Technique for Detection of Invisible Nuclei	304
10.4.2	Detection of Nuclei at Paramagnetic Centers: Paramagnetic Metal Ions.....	306
10.4.3	NMR Spectra of Paramagnetic Solids: General Aspects and Study Strategies	308
10.4.3.1	NMR Spectra of Quadrupolar Nuclei in Paramagnetic Solids.....	310
10.4.3.2	Common Strategies in Structural Studies of Paramagnetic Solids	313
10.5	Nuclear Relaxation in Paramagnetic Solids: Applications....	316
10.5.1	Strategy for Relaxation Studies of Paramagnetic Solids.....	317
	References and Recommended Literature.....	323
	Concluding Remarks	325
	Index.....	327