

# Modern NMR Techniques for Chemistry Research

ANDREW E. DEROME

The Dyson Perrins Laboratory,  
University of Oxford, UK



**PERGAMON PRESS**

OXFORD · NEW YORK · BEIJING · FRANKFURT  
SÃO PAULO · SYDNEY · TOKYO · TORONTO

# Contents

<b>Introduction, <i>Sir Rex Richards</i></b>	<b>xvii</b>
<b>1 What This Book Is About</b>	<b>1</b>
1.1 INTRODUCTION	1
1.2 WHAT YOU NEED TO KNOW	3
1.3 WHAT IS IN THE BOOK	3
1.4 WHAT CAN BE DONE WITH NMR	5
1.5 A SHORT TOUR ROUND AN NMR SPECTROMETER	6
REFERENCE	8
<b>2 Why Bother With Pulse NMR</b>	<b>9</b>
2.1 INTRODUCTION	9
2.2 THE TUNING OF BELLS	11
2.3 PULSE NMR	11
2.3.1 Introduction	11
2.3.2 Stimulating the Sample	12
2.3.3 Time and Frequency	12
2.4 PRACTICAL IMPLEMENTATION OF PULSE NMR	14
2.4.1 Introduction	14
2.4.2 Detection and Acquisition	14
<i>Introduction</i>	14
<i>Sampling the signals</i>	15
<i>Controlling the bandwidth</i>	17
2.4.3 Transformation	19
2.5 WORKING WITH FT NMR	20
2.5.1 Introduction	20
2.5.2 Digital Resolution and Acquisition Time	21
<i>Introduction</i>	21
<i>Zero-filling</i>	22
2.5.3 Truncation and Apodisation	22
2.5.4 Window Functions	24
<i>Introduction</i>	24
<i>Sensitivity - the matched filter</i>	24
<i>Resolution - the Lorentz - Gauss transformation</i>	25
2.5.5 Spotting Folded Peaks	27
REFERENCES	29

<b>3</b>	<b>Basic Experimental Methods</b>	<b>31</b>
3.1	INTRODUCTION	31
3.2	SAMPLE PREPARATION	31
3.2.1	Introduction	31
3.2.2	Choice of Solvent	31
3.2.3	The NMR Tube	36
3.2.4	Sample Volume	36
3.2.5	Sample Handling	37
3.2.6	Nuclei Other Than Protons	37
3.3	ACHIEVING RESOLUTION	38
3.3.1	Introduction	38
3.3.2	Criteria of Resolution	38
3.3.3	Factors Affecting Resolution	40
3.3.4	Shimming	42
	<i>Introduction</i>	42
	<i>The shims</i>	42
	<i>The deuterium lock</i>	44
	<i>Adjusting the shims</i>	46
	<i>Shimming using the FID</i>	49
	<i>Shimming unlocked</i>	50
3.4	ACHIEVING SENSITIVITY	50
3.4.1	Introduction	50
3.4.2	Criteria of Sensitivity	50
3.4.3	Factors Affecting Sensitivity	54
	<i>The probe</i>	54
	<i>Tuning it up</i>	56
	<i>Dynamic range and ADC resolution</i>	58
	REFERENCES	61
<b>4</b>	<b>Describing Pulse NMR</b>	<b>63</b>
4.1	INTRODUCTION	61
4.2	THE COMPONENTS OF THE EXPERIMENT	61
4.2.1	Introduction	61
4.2.2	The Nuclei	62
4.2.3	The Radio-frequency Field	65
4.2.4	The Rotating Frame	65
4.2.5	A Pulse!	67
4.2.6	Vectors and energy levels	68
4.3	REALISTIC EXPERIMENTS	69
4.3.1	Introduction	69
4.3.2	When the Pulse is Off-resonance	69
4.3.3	Several Frequencies At Once	72
4.3.4	Axes and Phases	73
4.3.5	Quadrature Detection	77
	<i>Introduction</i>	77
	<i>Problems with quad detection</i>	80
	<i>Phase cycling</i>	81
	<i>The Redfield method</i>	83
4.3.6	Phase Errors and Phase Correction	83

4.4	RELAXATION	85
4.4.1	Introduction	85
4.4.2	Towards Equilibrium	86
4.4.3	Relaxation in the $x$ - $y$ Plane	89
4.4.4	Spin Echoes	90
	<i>Introduction</i>	90
	<i>Spin echoes for measuring <math>T_2</math></i>	91
	<i>Useful properties of spin echoes</i>	93
4.5	DESCRIBING PULSE NMR	95
	REFERENCES	96

## 5 The Nuclear Overhauser Effect 97

5.1	INTRODUCTION	97
5.2	THE ORIGIN OF THE NUCLEAR OVERHAUSER EFFECT	98
5.2.1	Introduction	98
5.2.2	Pathways for Relaxation	98
5.2.3	Motives for Relaxation	101
	<i>Introduction</i>	101
	<i>Magnetic dipoles and dipolar coupling</i>	102
	<i>Relaxation through dipolar coupling</i>	103
	<i>Relaxation by other means</i>	105
5.2.4	The NOe and Internuclear Distance	106
	<i>Maximum <math>nOe</math>'s</i>	106
	<i>When the narrowing is not extreme</i>	106
	<i><math>nOe</math>'s in realistic systems</i>	107
	<i>Comparing two-spin <math>nOe</math>'s</i>	107
	<i>The <math>nOe</math> for several spins</i>	109
	<i>Two basic principles for multi-spin systems</i>	109
5.2.5	Transient NOe's	111
5.3	MEASURING NOE'S	112
5.3.1	Introduction	112
5.3.2	Sample Preparation	112
5.3.3	The Difference Method	113
	<i>Introduction</i>	113
	<i>Subtracting Lorentzian lines</i>	114
	<i>Optimum <math>nOe</math> difference spectroscopy</i>	117
	<i>Selectivity and the SPT problem</i>	118
	<i>Quantitative measurements</i>	119
5.3.4	Some Remarks about the Deuterium Lock	120
5.4	USING NOE'S	121
5.4.1	A Very Simple Case	121
5.4.2	A Test of the Three-spin Equation	122
5.4.3	A Real Problem	124
5.4.4	Heteronuclear NOe's	126
	REFERENCES	127

<b>6</b>	<b>Polarisation Transfer and Spectrum Editing</b>	<b>129</b>
6.1	INTRODUCTION	129
6.2	SELECTIVE POPULATION TRANSFER	130
6.3	INEPT	133
6.3.1	Introduction	133
	<i>The basic idea</i>	133
	<i>The natural I spin magnetisation</i>	135
	<i>Refocused INEPT</i>	136
6.3.2	Characteristics of INEPT Spectra	136
	<i>Effect on sensitivity</i>	136
	<i>Effect on coupled spectra</i>	139
6.3.3	The $\Delta$ Delay	141
	<i>Choice for optimum sensitivity</i>	141
	<i>Spectrum editing</i>	141
6.4	DEPT	143
6.4.1	Introduction	143
6.4.2	The DEPT Sequence (as a Multiple Quantum Filter)	144
6.4.3	Editing with DEPT	145
	<i>Introduction</i>	145
	<i>Editing</i>	145
	<i>Is editing accurate (does it matter?)</i>	146
6.4.4	DEPT for Coupled Spectra	147
6.4.5	Quadrupolar Nuclei	148
6.4.6	Doing it Backwards	149
	<i>Introduction</i>	149
	<i>Reverse DEPT</i>	150
	REFERENCES	151
<b>7</b>	<b>Further Experimental Methods</b>	<b>153</b>
7.1	INTRODUCTION	153
7.2	PULSE WIDTH AND FIELD STRENGTH	153
7.2.1	Introduction - the dB Scale	153
7.2.2	Pulses on the Observed Nucleus	154
	<i>With good sensitivity</i>	154
	<i>With poor sensitivity</i>	156
7.2.3	Pulses on Other Coupled Nuclei	156
7.2.4	Field Strength - Homonuclear	156
7.2.5	Field Strength - Heteronuclear	158
7.3	COPING WITH IMPERFECT PULSES	159
7.3.1	Introduction	159
7.3.2	Composite Pulses	159
7.4	BROADBAND DECOUPLING	162

7.5	RELAXATION AND REPETITION	164
7.5.1	Introduction	164
7.5.2	Pulse Width and Repetition Rate	165
7.5.3	Quick $T_1$ Determination	166
7.6	QUANTITATIVE INTENSITY MEASUREMENTS	168
7.6.1	Introduction	168
7.6.2	Making the Signals Proportional to the Number of Nuclei	168
7.6.3	Sampling the Data	169
7.6.4	Other Instrumental Problems	170
7.7	SELECTIVE EXCITATION AND SUPPRESSION	172
7.7.1	Introduction	172
7.7.2	Peak Suppression	172
	<i>By pre-saturation</i>	172
	<i>By tailored excitation</i>	173
7.7.3	Selective Excitation	176
	<i>With soft pulses</i>	176
	<i>With DANTE</i>	177
7.8	SOME SPECTROMETER TESTS TO TRY	178
	REFERENCES	181

## 8 Homonuclear Shift Correlation 183

8.1	INTRODUCTION	183
8.2	FREQUENCY LABELLING	184
8.3	JEENER'S EXPERIMENT	187
8.3.1	Introduction	187
8.3.2	A CW-FT 2D Experiment	187
8.3.3	Magnetisation is Transferred	188
8.3.4	Two Real Examples	190
8.3.5	Details of the COSY Experiment	197
	<i>Introduction</i>	197
	<i>Effect of longitudinal relaxation</i>	198
	<i>Eliminating <math>v_2</math> artefacts</i>	200
	<i>Quad detection in <math>v_1</math></i>	201
	<i>Echo or anti-echo selection</i>	204
	<i>Phase in two dimensions</i>	207
	<i>Relative phases in phase-sensitive COSY</i>	209
	<i>Digital resolution and acquisition times</i>	211
	<i>How long will it take</i>	215
	<i>Another look at magnetisation transfer</i>	215
8.3.6	Working With COSY	217
	<i>Using the phase information</i>	217
	<i>Measuring coupling constants</i>	221
	<i>Disappearing cross peaks</i>	221
	<i>Noise in two dimensions</i>	222
	<i>Folding in two dimensions</i>	223
	<i>Symmetrisation</i>	224
	<i>Nuclei other than protons</i>	225

8.4	EXPERIMENTS RELATED TO COSY	227
8.4.1	COSY-45	227
8.4.2	Detection of Small Couplings	227
8.4.3	Multiple Quantum Filtration	230
8.4.4	Relayed Coherence Transfer	232
8.5	OTHER HOMONUCLEAR SHIFT CORRELATION EXPERIMENTS	234
8.5.1	INADEQUATE	234
	<i>Introduction</i>	234
	<i>INADEQUATE-2D spectra</i>	235
	<i>Details of INADEQUATE-2D</i>	236
	<i>The original INADEQUATE experiment</i>	238
8.5.2	NOESY or Exchange Spectroscopy	239
	<i>Introduction</i>	239
	<i>Choosing <math>\tau_m</math></i>	240
	<i>Problems due to J-coupling</i>	241
	<i>Examples</i>	242
	REFERENCES	243
<b>9</b>	<b>Heteronuclear Shift Correlation</b>	<b>245</b>
9.1	INTRODUCTION	245
9.2	DETAILS OF HSC	246
9.2.1	Eliminating Various Couplings	246
	<i>Introduction</i>	246
	<i>Eliminating the coupling in <math>\nu_2</math></i>	246
	<i>Eliminating the coupling in <math>\nu_1</math></i>	247
9.2.2	Other Experimental Aspects	248
	<i>Phase cycle</i>	248
	<i>Acquisition times and repetition rate</i>	248
9.2.3	Using HSC	249
9.3	EXPERIMENTS RELATED TO HSC	252
9.3.1	HSC + Broadband Homonuclear $\nu_1$ Decoupling	252
9.3.2	Small Couplings - COLOC	254
9.4	RELAYED COHERENCE TRANSFER	255
9.4.1	Introduction	255
9.4.2	H-H-C Relay	255
9.4.2	Using RCT	256
	REFERENCES	257
<b>10</b>	<b>Spin Echoes and J-Spectroscopy</b>	<b>259</b>
10.1	INTRODUCTION	259
10.2	HETERONUCLEAR J-MODULATED SPIN ECHOES	259
10.2.1	Introduction	259
10.2.2	Spin Echo Difference	261

10.3	THE HETERONUCLEAR <i>J</i> -SPECTRUM	264
10.3.1	Introduction	264
10.3.2	Examples of Heteronuclear <i>J</i> -Spectra	265
	<i>With high <math>\nu_1</math> resolution</i>	266
	<i>With low <math>\nu_1</math> resolution</i>	267
10.3.3	Experimental Aspects	268
	<i>EXORCYCLE and composite <math>\pi</math> pulses</i>	268
	<i>Sign discrimination and lineshape</i>	269
10.4	THE HOMONUCLEAR <i>J</i> -SPECTRUM	270
10.4.1	Introduction	270
10.4.2	Tilting <i>J</i> -spectra	271
10.4.3	The Indirect <i>J</i> -spectrum	273
	REFERENCES	274
	<b>Index</b>	<b>277</b>