## C. P. Slichter

## Principles of Magnetic Resonance

Third Enlarged and Updated Edition

With 185 Figures

Springer-Verlag
Berlin Heidelberg New York
London Paris Tokyo
Hong Kong Barcelona
Budapest

## **Contents**

1.	Elem	ents of Resonance	1
	1.1	Introduction	1
	1.2	Simple Resonance Theory	2
	1.3	Absorption of Energy and Spin-Lattice Relaxation	4
2.	Basic Theory		11
	2.1	Motion of Isolated Spins-Classical Treatment	11
	2.2	Quantum Mechanical Description of Spin in a Static Field	13
	2.3	Equations of Motion of the Expectation Value	17
	2.4	Effect of Alternating Magnetic Fields	20
	2.5	Exponential Operators	25
	2.6	Quantum Mechanical Treatment of a Rotating Magnetic Field	29
	2.7	Bloch Equations	33
	2.8	Solution of the Bloch Equations for Low $H_1$	35
	2.9	Spin Echoes	39
	2.10	Quantum Mechanical Treatment of the Spin Echo	46
	2.11	Relationship Between Transient and Steady-State Response	
		of a System and of the Real and Imaginary Parts	
		of the Susceptibility	51
	2.12	Atomic Theory of Absorption and Dispersion	59
3.	Magnetic Dipolar Broadening of Rigid Lattices		65
	3.1	Introduction	65
	3.2	Basic Interaction	66
	3.3	Method of Moments	71
	3.4	Example of the Use of Second Moments	80
4.	Magnetic Interactions of Nuclei with Electrons 8		
	4.1	Introduction	87
	4.2	Experimental Facts About Chemical Shifts	88
	4.3	Quenching of Orbital Motion	89
	4.4	Formal Theory of Chemical Shifts	92
	4.5	Computation of Current Density	96
	4.6		108
	47	Knight Shift	113

	4.8	Single Crystal Spectra	127		
	4.9	Second-Order Spin Effects-Indirect Nuclear Coupling	131		
5.	Spin-Lattice Relaxation and Motional Narrowing				
	of Re	sonance Lines	145		
	5.1	Introduction	145		
	5.2	Relaxation of a System Described by a Spin Temperature	146		
	5.3	Relaxation of Nuclei in a Metal	151		
	5.4	Density Matrix – General Equations	157		
	5.5	The Rotating Coordinate Transformation	165		
	5.6	Spin Echoes Using the Density Matrix	169		
	5.7	The Response to a $\delta$ -Function	174		
	5.8	The Response to a $\pi/2$ Pulse: Fourier Transform NMR	179		
	5.9	The Density Matrix of a Two-Level System	186		
	5.10	Density Matrix – An Introductory Example	190		
	5.11	Bloch-Wangsness-Redfield Theory	199		
	5.12	Example of Redfield Theory	206		
	5.13	Effect of Applied Alternating Fields	215		
6.	Spin	Temperature in Magnetism and in Magnetic Resonance	219		
	6.1	Introduction	219		
	6.2	A Prediction from the Bloch Equations	220		
	6.3	The Concept of Spin Temperature in the Laboratory Frame			
		in the Absence of Alternating Magnetic Fields	221		
	6.4	Adiabatic and Sudden Changes	223		
	6.5	Magnetic Resonance and Saturation	231		
	6.6	Redfield Theory Neglecting Lattice Coupling	234		
		6.6.1 Adiabatic Demagnetization in the Rotating Frame	235		
		6.6.2 Sudden Pulsing	237		
	6.7	The Approach to Equilibrium for Weak $H_1$	239		
	6.8	Conditions for Validity of the Redfield Hypothesis	241		
	6.9	Spin-Lattice Effects	242		
	6.10	Spin Locking, $T_{1\varrho}$ , and Slow Motion	244		
7.	Doub	le Resonance	247		
•	7.1	What Is Double Resonance and Why Do It?	247		
	7.2	Basic Elements of the Overhauser-Pound Family	2.,		
	7.2	of Double Resonance	248		
	7.3	Energy Levels and Transitions of a Model System	250		
	7.4	The Overhauser Effect	254		
	7.5	The Overhauser Effect in Liquids: The Nuclear	254		
	1.5	Overhauser Effect	257		
	7.6	Polarization by Forbidden Transitions: The Solid Effect	264		
	7.0 7.7	Electron-Nuclear Double Resonance (ENDOR)	266		
	1.1	Electron-rate at Double Resonance (ENDOR)	200		

	7.8	Bloembergen's Three-Level Maser	269
	7.9	The Problem of Sensitivity	270
	7.10	Cross-Relaxation Double Resonance	271
	7.11	The Bloembergen-Sorokin Experiment	275
	7.12	Hahn's Ingenious Concept	277
	7.13	The Quantum Description	279
	7.14	The Mixing Cycle and Its Equations	283
	7.15	Energy and Entropy	287
	7.16	The Effects of Spin-Lattice Relaxation	289
	7.17	The Pines-Gibby-Waugh Method of Cross Polarization	293
	7.18	Spin-Coherence Double Resonance – Introduction	295
	7.19	A Model System - An Elementary Experiment:	
		The S-Flip-Only Echo	296
	7.20	Spin Decoupling	303
	7.21	Spin Echo Double Resonance	311
	7.22	Two-Dimensional FT Spectra – The Basic Concept	319
	7.23	Two-Dimensional FT Spectra – Line Shapes	324
	7.24	Formal Theoretical Apparatus I-The Time Development	
		of the Density Matrix	325
	7.25	Coherence Transfer	331
	7.26	Formal Theoretical Apparatus II – The Product Operator	
		Method	344
	7.27	The Jeener Shift Correlation (COSY) Experiment	350
	7.28	Magnetic Resonance Imaging	357
8.	Adva	nced Concepts in Pulsed Magnetic Resonance	367
	8.1	Introduction	367
	8.2	The Carr-Purcell Sequence	367
	8.3	The Phase Alternation and Meiboom-Gill Methods	369
	8.4	Refocusing Dipolar Coupling	371
	8.5	Solid Echoes	371
	8.6	The Jeener-Broekaert Sequence for Creating Dipolar Order	380
	8.7	The Magic Angle in the Rotating Frame –	
	0.,	The Lee-Goldburg Experiment	384
	8.8	Magic Echoes	388
	8.9	Magic Angle Spinning	392
	8.10	The Relation of Spin-Flip Narrowing to Motional Narrowing	406
	8.11	The Formal Description of Spin-Flip Narrowing	409
	8.12	Observation of the Spin-Flip Narrowing	416
	8.13	Real Pulses and Sequences	421
	0.15	8.13.1 Avoiding a z-Axis Rotation	421
		<u> </u>	421
	011	8.13.2 Nonideality of Pulses	
	8.14	Analysis of and More Uses for Pulse Sequence	423

9.	Multi	ple Quantum Coherence	431
	9.1	Introduction	431
	9.2	The Feasibility of Generating Multiple Quantum Coherence-	
		Frequency Selective Pumping	434
	9.3	Nonselective Excitation	444
		9.3.1 The Need for Nonselective Excitation	444
		9.3.2 Generating Multiple Quantum Coherence	445
		9.3.3 Evolution, Mixing, and Detection of Multiple	
		Quantum Coherence	449
		9.3.4 Three or More Spins	455
		9.3.5 Selecting the Signal of a Particular Order of Coherence	463
	9.4	High Orders of Coherence	470
	7.7	9.4.1 Generating a Desired Order of Coherence	471
		9.4.2 Mixing to Detect High Orders of Coherence	480
		7.4.2 Mixing to Detect High Orders of Concrence	700
10	Flectr	ric Quadrupole Effects	485
10.	10.1	Introduction	485
	10.1	Quadrupole Hamiltonian – Part 1	486
	10.2	Clebsch-Gordan Coefficients, Irreducible Tensor Operators,	400
	10.5	and the Wigner-Eckart Theorem	489
	10.4	Quadrupole Hamiltonian – Part 2	494
	10.4	Examples at Strong and Weak Magnetic Fields	497
	10.5	Computation of Field Gradients	500
	10.0	Computation of Field Oracletics	300
11.	Electr	on Spin Resonance	503
	11.1	Introduction	503
	11.2	Example of Spin-Orbit Coupling and Crystalline Fields	505
	11.3	Hyperfine Structure	516
	11.4	Electron Spin Echoes	524
	11.5	$V_k$ Center	533
	11.5	V Conto	333
12.	Sumn	nary	555
	Ou III.		555
Pro	blems		557
Api	pendix	es	579
		Theorem About Exponential Operators	579
		me Further Expressions for the Susceptibility	580
		erivation of the Correlation Function for a Field	500
		that Jumps Randomly Between $\pm h_0$	584
		Theorem from Perturbation Theory	585
		e High Temperature Approximation	589
		e Effects of Changing the Precession Frequency –	209
		ing NMR to Study Rate Phenomena	592
	US	mg munic to other hate inchestions	374

G. Diffusion in an Inhomogeneous Magnetic Field	597
H. The Equivalence of Three Quantum Mechanics Problems	601
I. Powder Patterns	605
J. Time-Dependent Hamiltonians	616
K. Correction Terms in Average Hamiltonian Theory-	
The Magnus Expansion	623
Selected Bibliography	629
References	639
References	035
Author Index	647
	, , ,
Subject Index	651