

Quantum Spin Microscopy's Emerging Methods, Roadmaps, and Enterprises

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Achieving three-dimensional, in-depth, atomic-resolution biological microscopy of undenatured specimens is one of the oldest dreams of science. Recently an IBM team led by Dan Rugar and John Mamin has taken us substantially closer to this goal [1] using magnetic resonance force microscopy (MRFM) to obtain three-dimensional images of tobacco mosaic viruses having voxel resolution down to ~ 4 nm. A 1946 letter from John von Neumann to Norbert Wiener [2] invites Wiener to consider whether comprehensive atomic-resolution biological microscopy might be achieved “by developments of which we can already foresee the character, the caliber, and the duration. And are the latter two not excessive and impractical?” Obtaining reliable answers to von Neumann’s question is the overall objective of this work.

Emerging Methods Our practical focus is the development of numerical algorithms for the end-to-end simulation of atomic-resolution quantum spin microscopy [3], with emphasis upon polarization transport processes. Here “end-to-end” means an integrated simulation of all the dynamical elements of a quantum spin microscope, from macroscopic elements like sample positioners, to microscopic elements like force microscope cantilevers, to fully quantum elements, like the individual spins in supramolecular structures. In brief, the simulation strategy is to transcribe Hilbert-space descriptions of quantum dynamics into the geometric language of symplectic flows and Lindbladian stochastic processes [4, 5].

Emerging Roadmaps and Enterprises As large-scale quantum simulation methods become more efficient, quantum systems engineering methods become more practical; in consequence the present decade is effectively a “Sputnik Moment” for magnetic resonance research and enterprise that is witnessing a “Cambrian Explosion” of diverse experimental methods and theoretical ideas. Our present theoretical and experimental investigations are exploring the physics of polarization transport processes in large magnetic gradients, with a view toward achieving by dynamical nuclear spin polarization an MRFM signal strength sufficient for imaging with (0.5 nm)³ voxel resolution, sufficient for the direct imaging of (for example) the changes in chromatin architecture that are associated to cell differentiation in regenerative healing processes.

Acknowledgements This work is dedicated to the families of the *Ceremony in Honor of Wounded Marines*, 12 May 2006, Marine Corps Barracks, Washington, DC. This research is supported by the Army Research Office (ARO) under MURI program # W911NF-05-1-0403. Presented as poster #PA-15, 52nd ENC, April 10–15 2011, Asilomar CA.

- [1] C. L. Degen, M. Poggio, H. J. Mamin, C. T. Retner, and D. Rugar. Nanoscale magnetic resonance imaging. *Proc. Nat. Acad. Sci. USA*, 106(13):1313–1317, 2009.
[2] J. von Neumann. Letter to Norbert Wiener from John von Neumann. In V. Mandelker and P. R. Maasi, editors, *Proceedings of the Norbert Wiener Congress*, 1994, volume 52 of *Proc. Symp. Appl. Math.*, pages 506–512. AMS, 1997.
[3] J. A. Sidles. Spin microscopy’s heritage, achievements, and prospects. *Proc. Nat. Acad. Sci.*, 106(8):2477–8, 2009.
[4] J. A. Sidles, J. L. Garbini, L. E. Harrell, K. Q. Heo, J. P. Jacky, J. R. Matoska, A. G. Norman, and R. A. Picone. Practical recipes for the model order reduction, dynamical simulation, and compressive sampling of large-scale open quantum systems. *New Journal of Physics*, 11(6):065002 (9pp), 2009.
[5] J. A. Sidles, J. L. Garbini, J. P. Jacky, R. A. R. Picone, and S. A. Harska. Elements of naturality in dynamical simulation frameworks for Hamiltonian, thermodynamic, and Lindbladian flows on classical and quantum state-spaces. *arXiv e-print*, July 2010. arxiv.org/1007.1958.

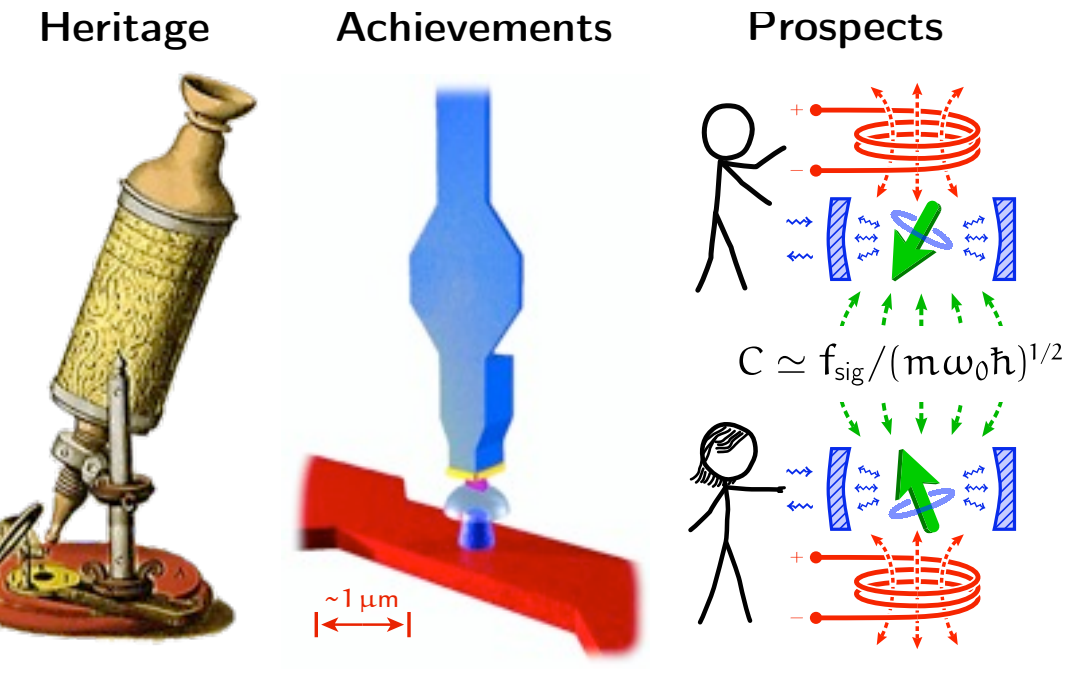


Figure 1 Magnetic resonance microscopes can be viewed as communication channels between the sample and microscope. Present microscopes are far from quantum limits [3].

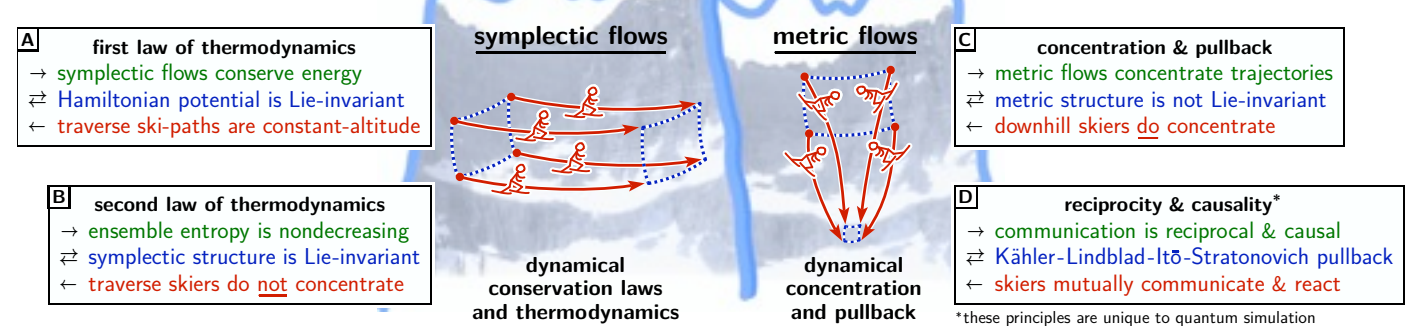


Figure 2 Dynamical processes in spin microscopy are naturally described in terms of symplectic flows (A–B) that respect thermodynamical laws, and metric flows (C–D) that describe measurement, control, and noise processes. In consequence of compressive Lindbladian dynamics, numerical trajectory integration is efficient even for systems of hundreds of spins [5].

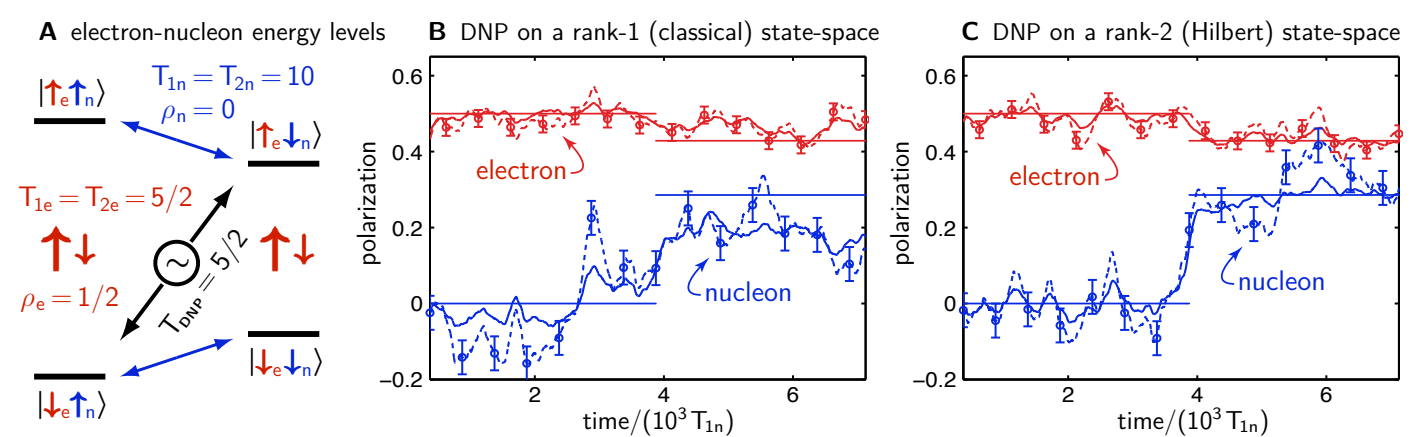


Figure 3 The large magnetic gradients of spin microscopes are a new environment for polarization transport. Novel (and potentially practical) mechanisms for dynamical spin polarization are associated to these gradients [5].

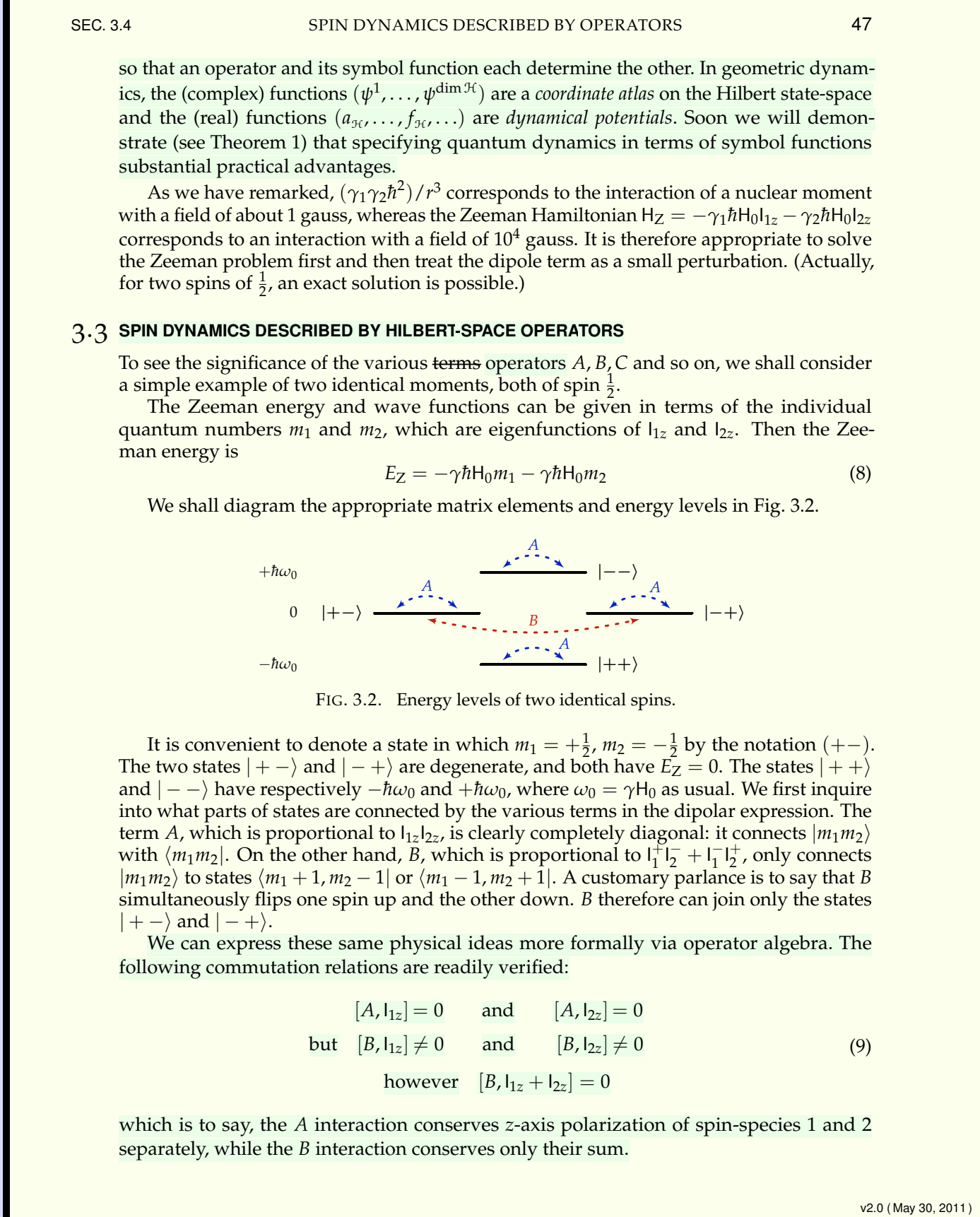
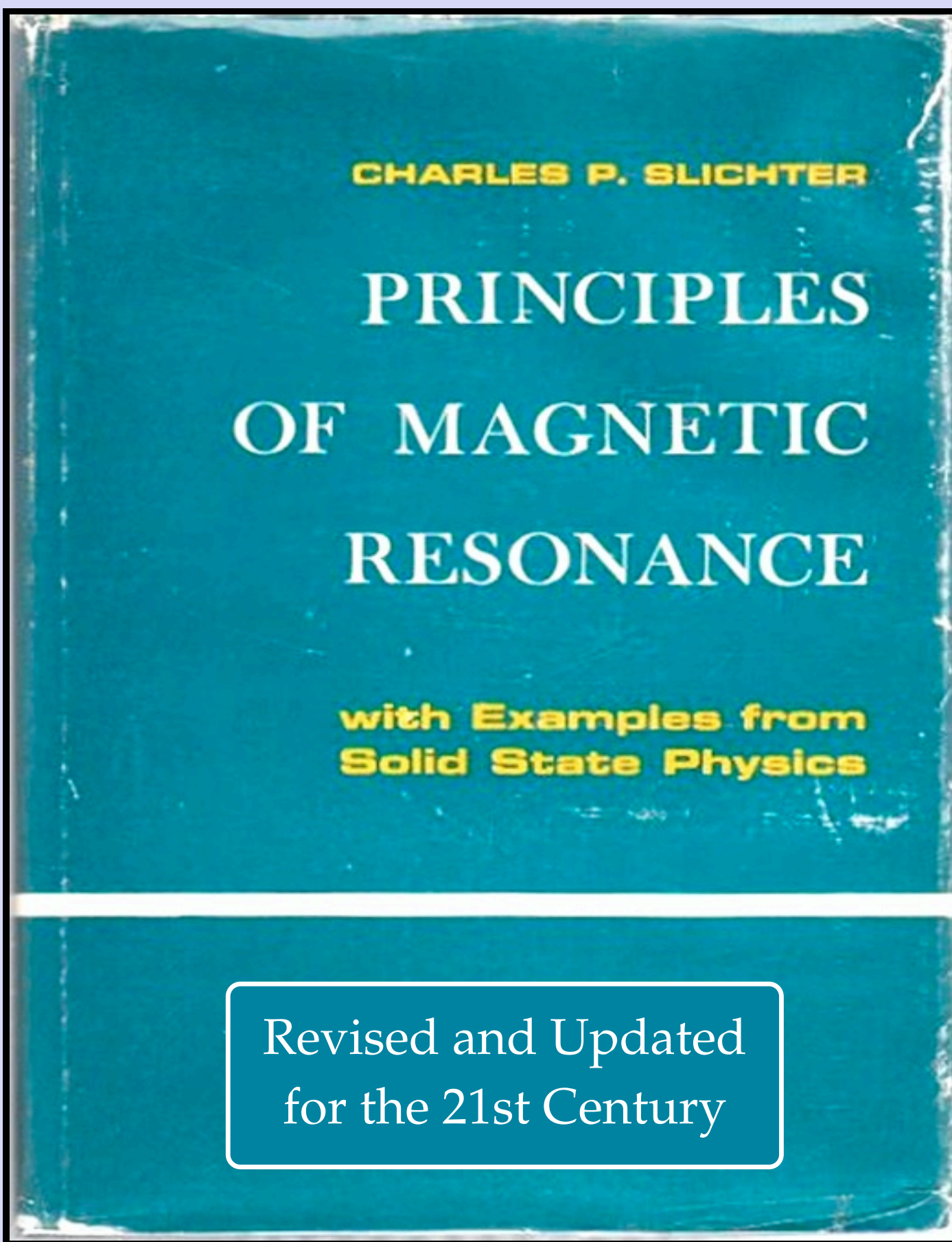


Figure 3.2. Energy levels of two identical spins.

MAGNETIC DIPOLAR DYNAMICS CHAPTER 3

CHAPTER 3

MAGNETIC DIPOLAR BROADENING AND TRANSPORT DYNAMICS OF RIGID LATTICES

(AS IMAGINED FOR THE 21ST CENTURY)

KEY: [Slichter's 1963 text (verbatim) is typeset on a yellow background]
[added content for the 21st ENC is highlighted in green]
[marginal notes are highlighted in red]

A tribute to Charles P. Slichter

3-1 INTRODUCTION

Note 1 This chapter will consider magnetic dipolar interactions in two idealized limits: the zero-gradient limit of spectral magnetic resonance applications, and the strong-gradient limit of nanometer-scale imaging applications.¹

Note 2 In spectral applications a number of physical phenomena may contribute to the width of a resonance line. The most prosaic is the lack of homogeneity of the applied static magnetic field. By dint of hard work and clever techniques, this source can be reduced to a few milligauss out of 10³ gauss, although more typically magnet homogeneities are a few tenths of a gauss. The homogeneity depends on sample size. Typical samples have a volume between 0.1 cc to several cubic centimeters. Of course fields of ultrahigh homogeneity place severe requirements on the frequency stability of the oscillator used to generate the alternating fields. Although these matters are of great technical importance, we shall not discuss them here. If a nucleus possesses a non-vanishing electric quadrupole moment, the degeneracy of the resonance frequencies between different m -values may be lifted, giving rise to either resolved or unresolved splittings. The fact that T_1 processes produce an equilibrium population by balancing rates of transitions puts a limit on the lifetime of the Zeeman states, which effectively broadens the resonance lines by an energy of the order of \hbar/T_1 .

Similarly, in ultra-strong field gradients (of order gauss per angstrom) we see that polarization processes are associated to conservation laws that are exact for purely dipolar interactions in purely linear gradients. Of course, in real life these conservation laws are only approximately exact, in consequence of nonlinear field geometries and various other factors.

Note 3 This is an optional extra from Chapter 3 of Slichter's *Principles of Magnetic Resonance* (1963), highlighted text is a modern perspective, written for posterity. *Quantum Spin Microscopy's Emerging Methods, Roadmaps, and Enterprises*, presented at the 52nd ENC, April 10–15, 2011, Asilomar CA, on the occasion of John Sidles sharing with Dan Rugar and John Mamin of IBM the Canby Lecture Prize for 2011. This work is dedicated to the families of the *Ceremony in Honor of Wounded Marines*, 12 May 2006, Marine Corps Barracks, Washington, DC. This research is supported by the Army Research Office (ARO) under MURI program W911NF-05-1-0403.

Revised and Updated for the 21st Century

MAGNETIC DIPOLAR DYNAMICS CHAPTER 3

CHAPTER 3

MAGNETIC DIPOLAR DYNAMICS DESCRIBED BY HILBERT-SPACE OPERATORS

Now we express the above operator commutation relations equivalently in terms of dynamical potentials. The rules for this conversion are simple²

operators \rightarrow symbol functions
commutators \rightarrow Poisson brackets

by which Eq. (9) becomes (with $h_{12} \rightarrow h_{12} = \langle \psi | h_{12} | \psi \rangle$, etc., as above)

$$\begin{aligned} (d_1, d_2)_{12} &= 0 \quad \text{and} \quad (d_1, d_2)_{12} = 0 \\ \text{but } (d_1, d_2)_{12} &\neq 0 \quad \text{and} \quad (d_1, d_2)_{12} \neq 0 \end{aligned}$$

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Here we have embraced the standard notation and idiom of geometric dynamics, in which ω_{12} is the canonical symplectic structure of Hilbert space (which we will give explicitly in Eq. 15), $(\cdot, \cdot)_{12}$ is the symplectic inner product that is induced by ω_{12}^* , and d is the exterior derivative.

It is customary practice in geometric dynamics that whenever functions (f, g, h) on a state-space satisfy $(df, dg)_{12} = h$, where ω is a symplectic structure, and h is said to be the Poisson bracket of f and g with respect to that symplectic structure. Furthermore, ω associates to every smooth function f a vector-valued tangent bundle $X_f = g_f^{-1} df$, which is known as a Hamiltonian flow with respect to f . Equivalently, one may sometimes refer to Poisson brackets and Hamiltonian flows.

$$\{f, g\}_{12} = (df, dg)_{12} \quad \text{and} \quad X_f \cdot \omega = h_f \omega = df$$

and thus we have for any vector field Y

$$\omega(X_f, Y) = df(Y) = \{f, Y\}_{12}$$

The connection to quantum physics upon a Hilbert space \mathcal{H} is established when we associate to our Hamiltonian operator H^{Hilb} a symbol function, $h^{\text{Hilb}} = \langle \psi | H^{\text{Hilb}} | \psi \rangle$; then $X_{h^{\text{Hilb}}}$ is the dynamical flow associated to the Schrödinger equation.

Given two symbol functions f and g , their Poisson bracket $\{f, g\}_{12} = (df, dg)_{12}$ specifies a third flow $X_{\{f, g\}_{12}}$ that is related to the Lie bracket $[X_f, X_g]$ by a well-known relation

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We observe that the Hilbert space operator commutation relation $[h_1, h_2] = 0$, is associated to the Lie bracket flow relation $[X_{h_1}, X_{h_2}] = X_0 = X_{h^{\text{Hilb}}}$. No confusion need arise as to whether $\{ \cdot, \cdot \}_{12}$ is an operator commutator versus a Lie bracket, as this will always be clear from the operators applied to the brackets.

²Our notation is that of John Lee's *Introduction to Smooth Manifolds*.

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Spin microscopy's heritage, achievements, and prospects

John A. Sidles¹
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Achieving three-dimensional, in-depth, atomic-resolution biological microscopy of undenatured specimens is one of the oldest dreams of science, and for good reason. Recently an IBM team led by Dan Rugar and John Mamin has taken us substantially closer to this goal [1] using magnetic resonance force microscopy (MRFM) to obtain three-dimensional images of tobacco mosaic viruses having voxel resolution down to ~ 4 nm. A 1946 letter from John von Neumann to Norbert Wiener [2] invites Wiener to consider whether comprehensive atomic-resolution biological microscopy might be achieved “by developments of which we can already foresee the character, the caliber, and the duration. And are the latter two not excessive and impractical?” Obtaining reliable answers to von Neumann’s question is the overall objective of this work.

Heritage Achievements Prospects

Figure 1. Spin microscopy’s heritage, achievements, and prospects. The large magnetic gradients of spin microscopes are a new environment for polarization transport. Novel (and potentially practical) mechanisms for dynamical spin polarization are associated to these gradients [5].

Figure 2. Dynamical processes in spin microscopy are naturally described in terms of symplectic flows (A–B) that respect thermodynamical laws, and metric flows (C–D) that describe measurement, control, and noise processes. In consequence of compressive Lindbladian dynamics, numerical trajectory integration is efficient even for systems of hundreds of spins [5].

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Spin microscopy's heritage, achievements, and prospects

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Achieving three-dimensional, in-depth, atomic-resolution biological microscopy of undenatured specimens is one of the oldest dreams of science, and for good reason. Recently an IBM team led by Dan Rugar and John Mamin has taken us substantially closer to this goal [1] using magnetic resonance force microscopy (MRFM) to obtain three-dimensional images of tobacco mosaic viruses having voxel resolution down to ~ 4 nm. A 1946 letter from John von Neumann to Norbert Wiener [2] invites Wiener to consider whether comprehensive atomic-resolution biological microscopy might be achieved “by developments of which we can already foresee the character, the caliber, and the duration. And are the latter two not excessive and impractical?” Obtaining reliable answers to von Neumann’s question is the overall objective of this work.

Heritage Achievements Prospects

Figure 1. Spin microscopy’s heritage, achievements, and prospects. The large magnetic gradients of spin microscopes are a new environment for polarization transport. Novel (and potentially practical) mechanisms for dynamical spin polarization are associated to these gradients [5].

Figure 2. Dynamical processes in spin microscopy are naturally described in terms of symplectic flows (A–B) that respect thermodynamical laws, and metric flows (C–D) that describe measurement, control, and noise processes. In consequence of compressive Lindbladian dynamics, numerical trajectory integration is efficient even for systems of hundreds of spins [5].

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