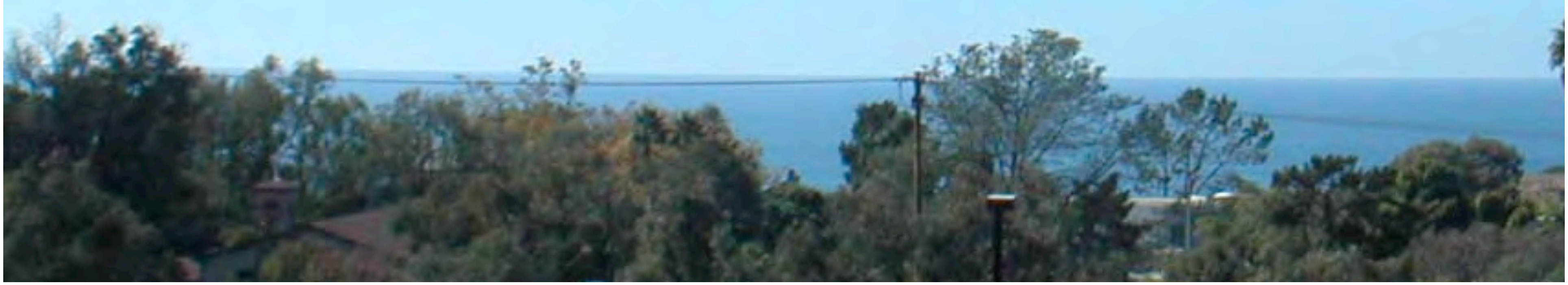
Winter School on Biomolecular Solid State NMR

January 20 - 25, 2008

Theory and Implementation of Techniques for Oriented Systems I

Stanley J. Opella

Department of Chemistry and Biochemistry
University of California, San Diego
La Jolla, California USA



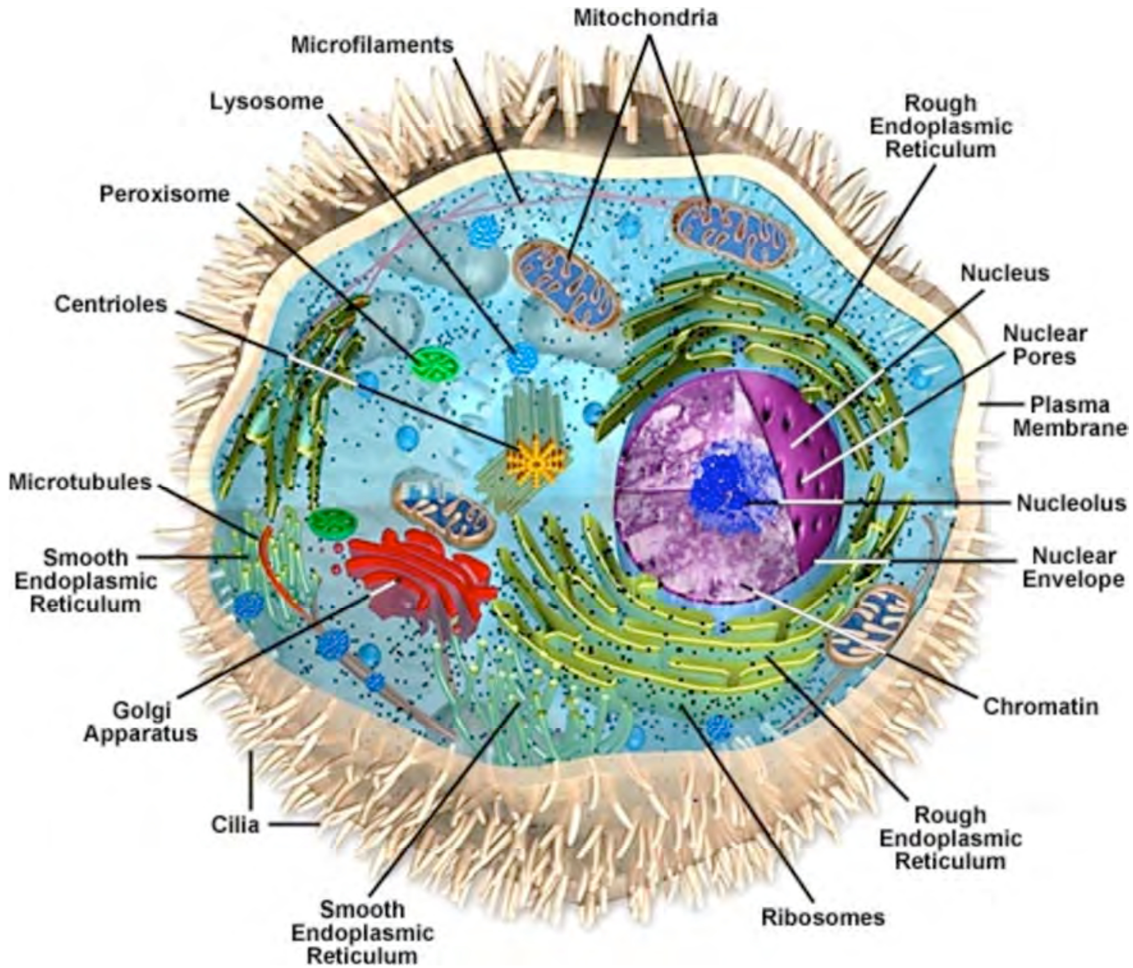
UCSD Center for NMR Spectroscopy and Imaging of Proteins

Training and Dissemination Activities of The Biotechnology Resource for NMR Molecular Imaging of Proteins

P41EB002031

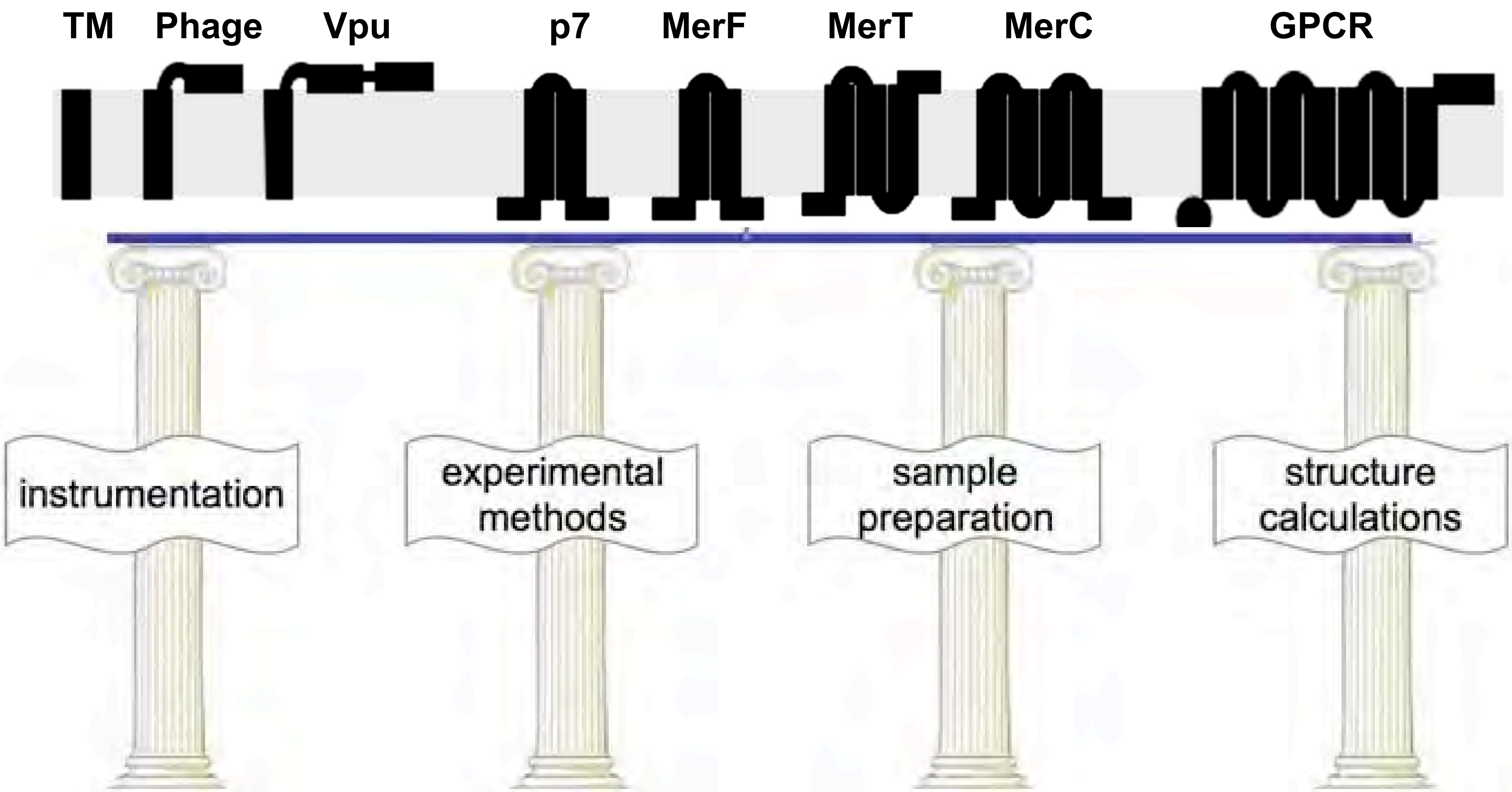
Introduction

The majority of proteins reside in membranes or other supramolecular assemblies, and are not soluble.

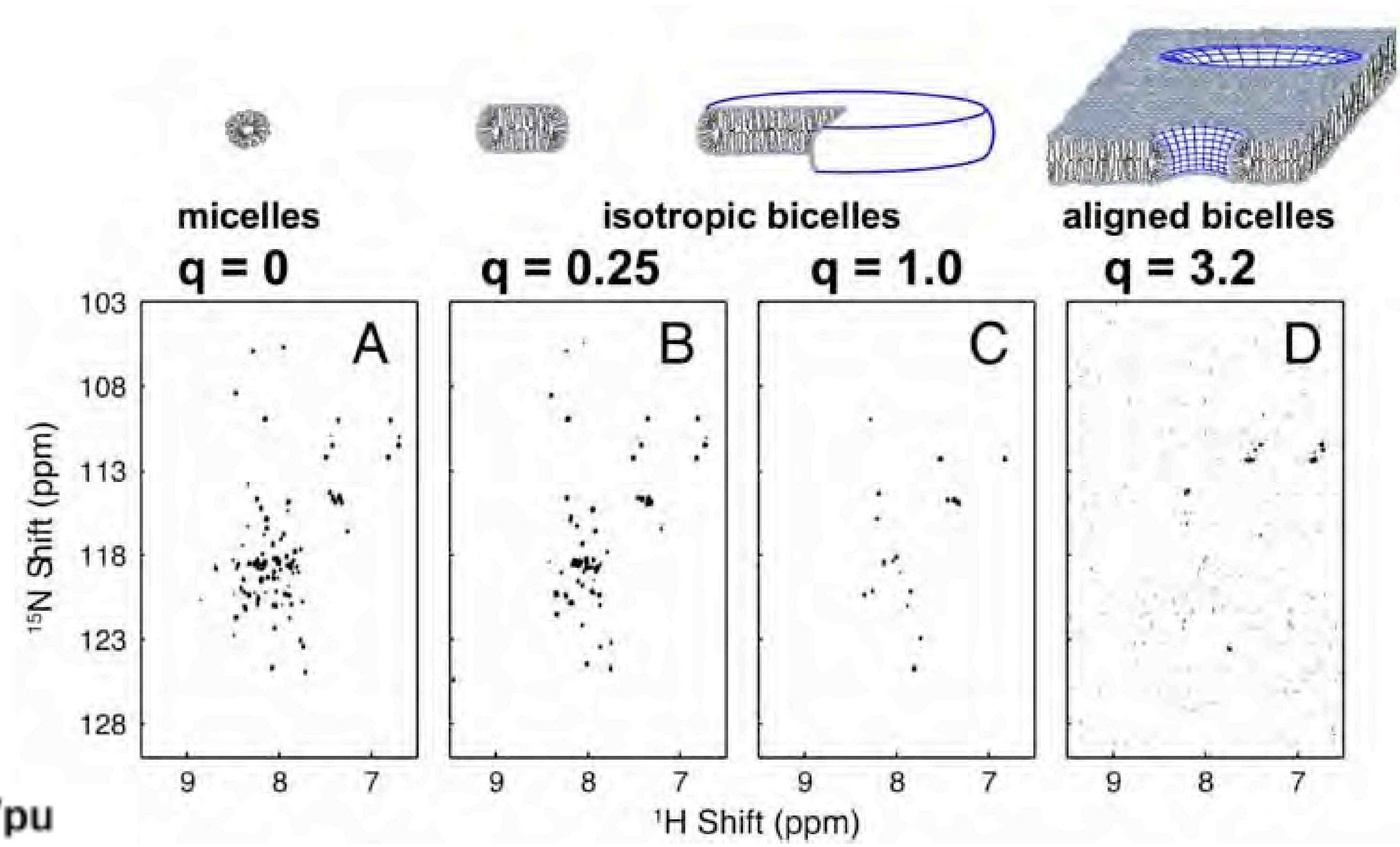


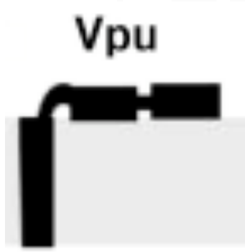
www.virtuallaboratory.net/biofundamentals/lecturenotes

Membrane protein structure determination rests on four pillars.



Solution-state NMR of membrane proteins is problematic in bilayer environments.





uniformly ^{15}N labeled Vpu

Basic requirements of an NMR approach to membrane proteins.

- Solve the correlation time problem.
  - High sensitivity.
  - High resolution.
- Determine protein structures.
  - Resolve resonances.
  - Assign resonances.
  - Measure frequencies.
  - Extract orientation and/or distance constraints.
  - Calculate structures.

Solid-state NMR spectroscopy

Proton-Enhanced Nuclear Induction Spectroscopy. A Method for High Resolution NMR of Dilute Spins in Solids*

A. PINES, M. G. GIBBY,† AND J. S. WAUGH

Department of Chemistry and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

in a 1 cm^3 sample. One can thus contemplate high resolution NMR of very rare spins and/or very small samples. Studies of chemical shift anisotropy of rare species (e.g., metals bound to proteins) or the dipolar structure of rare spin groups (e.g., ^{31}P in polyphosphate moieties) could be of value in structural studies.

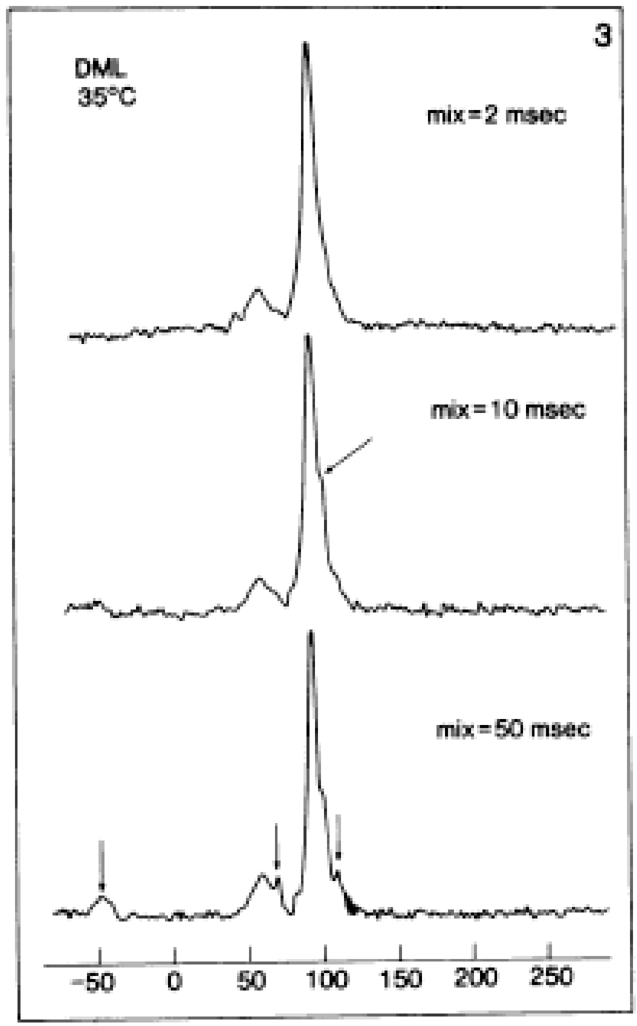
1972

Proton-Enhanced ^{13}C Nuclear Magnetic Resonance of Lipids and Biomembranes

(phospholipids/bilayers)

JULIO URBINA AND J. S. WAUGH

Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Mass. 02139



1974

Nuclear spin interactions are anisotropic.

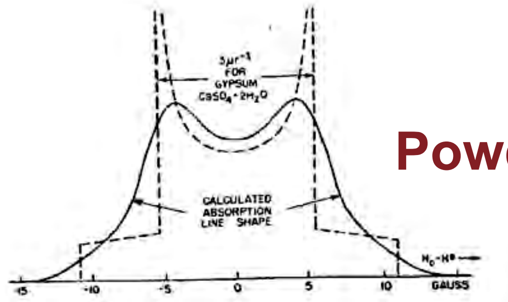
Proteins in supramolecular assemblies, e.g. membranes, typically reside in highly anisotropic physical environments that prevent rapid isotropic reorientation.

The control (attenuation and measurement) of dipole-dipole couplings is essential.

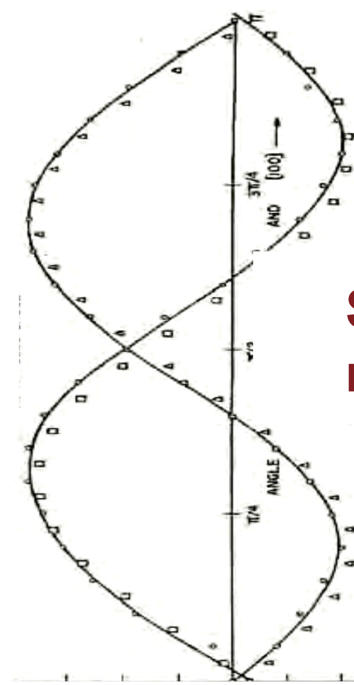
The dipole-dipole interaction is anisotropic.

Nuclear Resonance Absorption in Hydrated Crystals: Fine Structure of the Proton Line

G. E. PAKE*



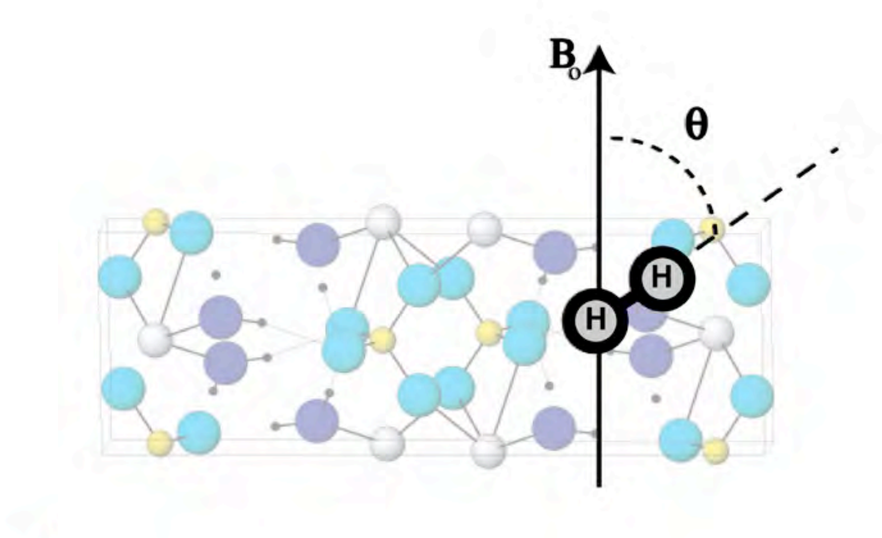
Powder pattern.

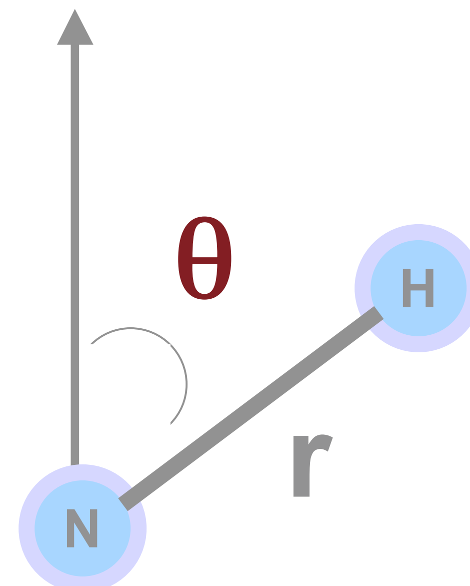


Single crystal rotation pattern.

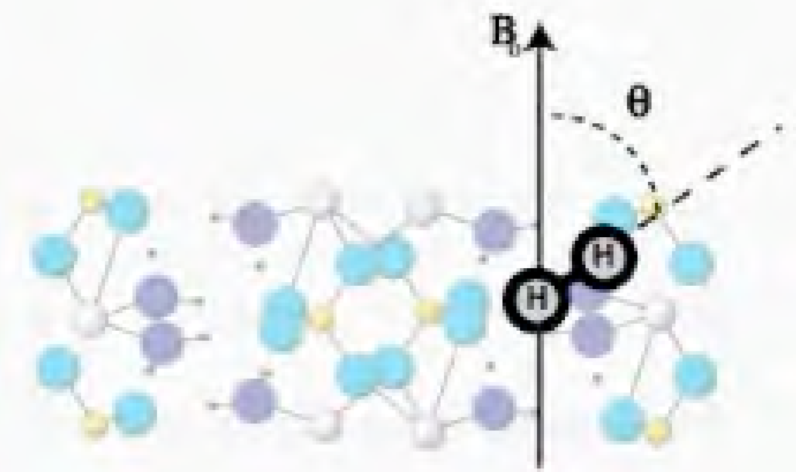
1948

^1H - ^1H spins in water in gypsum. ^1H are "dilute" by space.



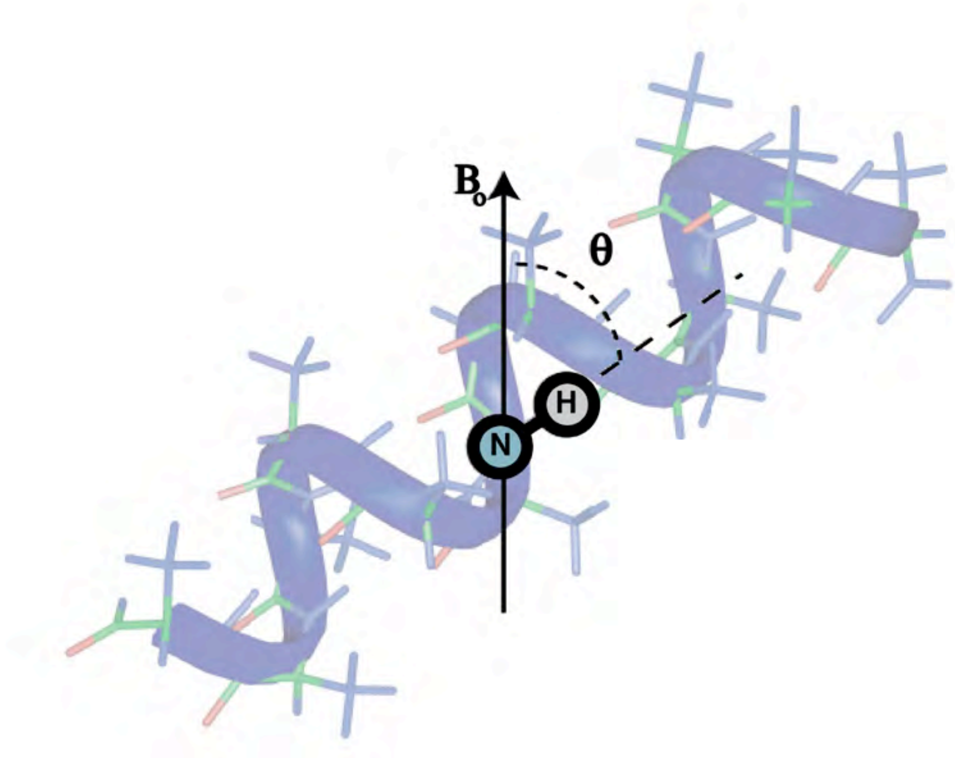


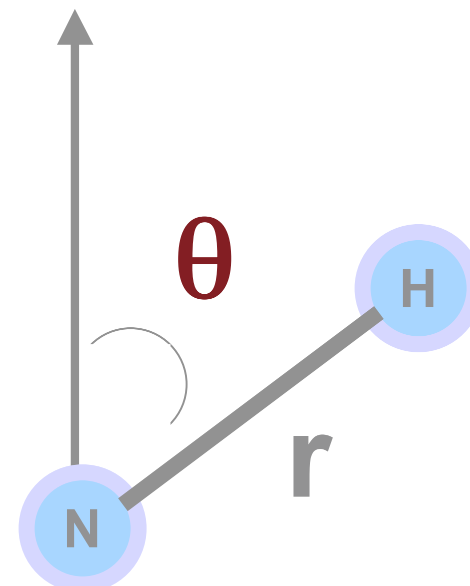
$$\Delta\nu \propto \frac{(3\cos^2\theta - 1)}{r^3}$$



B0
θ
H
H

^{1}H - ^{15}N spins in peptide bond. ^{15}N is "dilute" by space. ^{1}H is "abundant" in large bath.



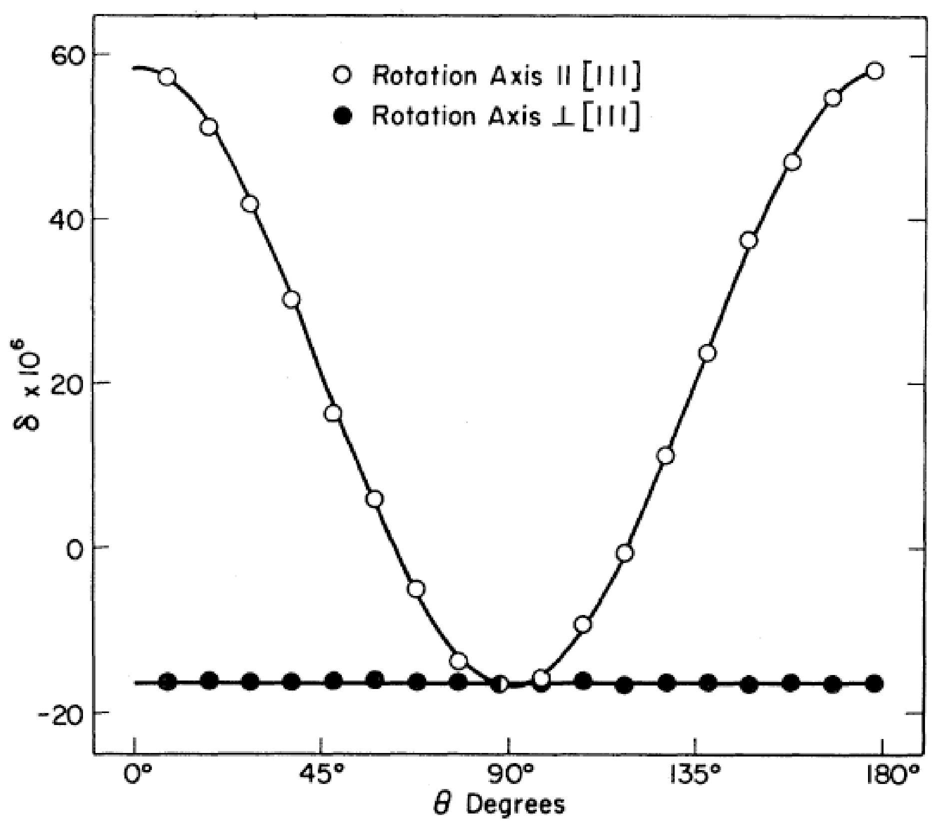


$$\Delta\nu \propto \frac{(3\cos^2\theta - 1)}{r^3}$$

The chemical shift interaction is anisotropic. ^{13}C is "dilute" by isotopic composition. There are no ^{1}H.

ANISOTROPY OF THE C^{13} CHEMICAL SHIFT IN CALCITE

Paul C. Lauterbur

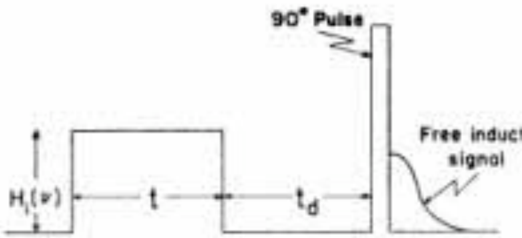


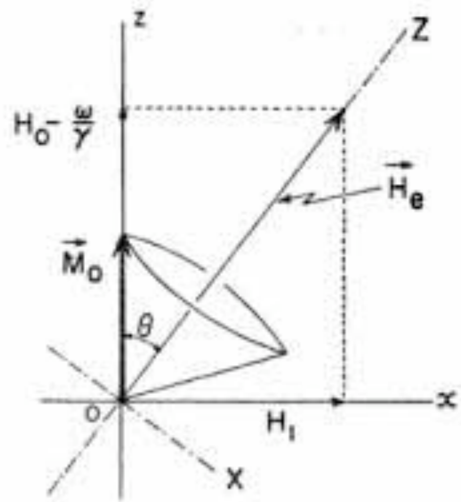
1958

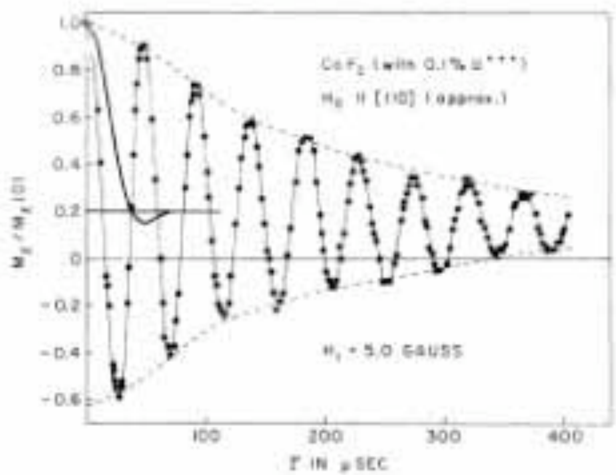
Attenuation of dipole-dipole couplings

Nuclear-Magnetic-Resonance Line Narrowing by a Rotating rf Field*†

Moses Lee‡ and Walter I. Goldburg
Department of Physics, University of Pittsburgh, Pittsburgh, Pennsylvania
(Received 1 June 1965)





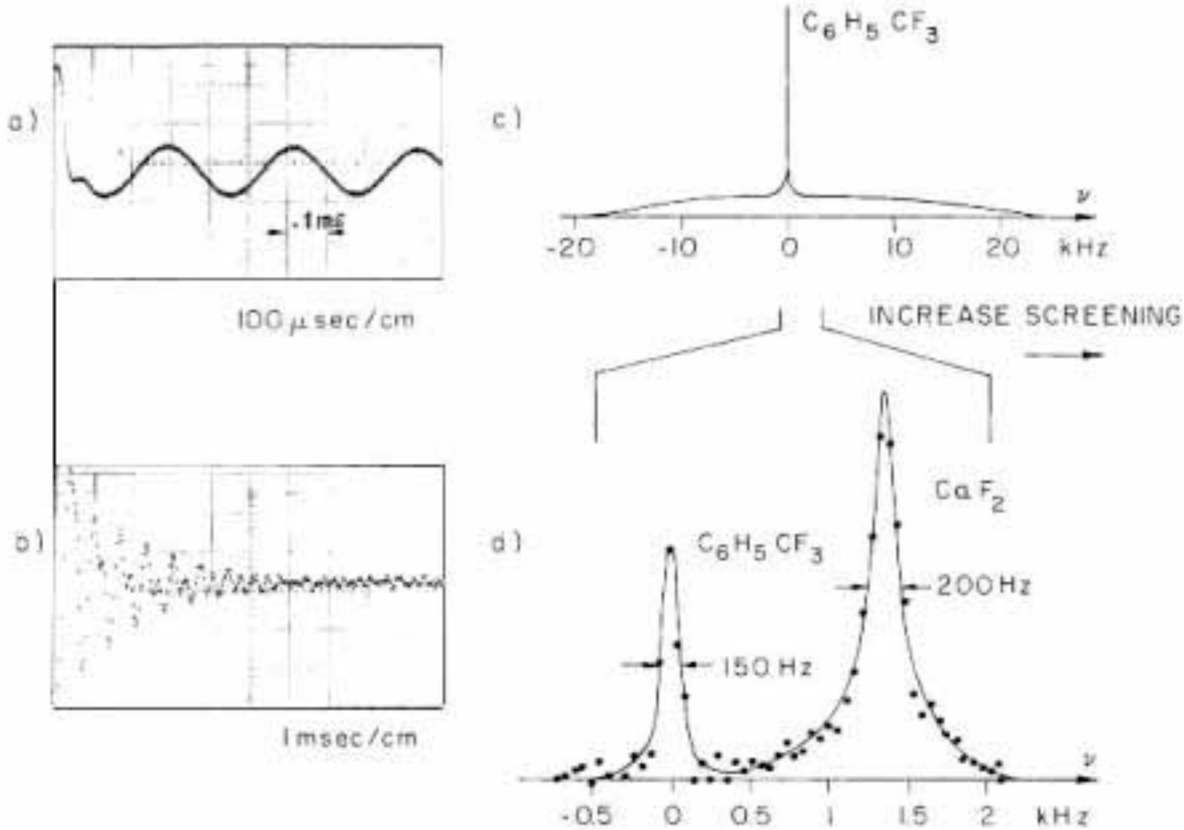


1965

WaHuHa

APPROACH TO HIGH-RESOLUTION nmr IN SOLIDS*

J. S. Waugh, L. M. Huber, and U. Haeberlen†
Department of Chemistry and Research Laboratory of Electronics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139



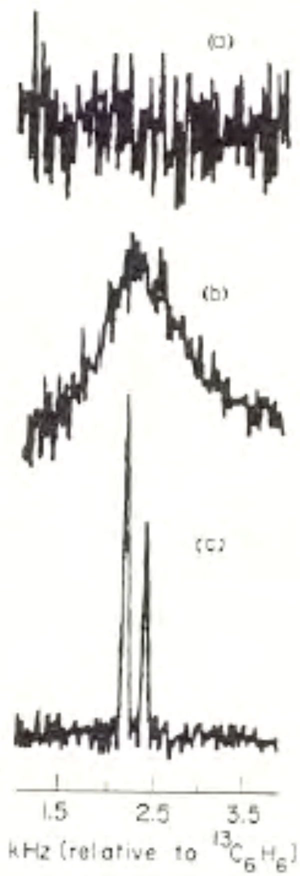
1968

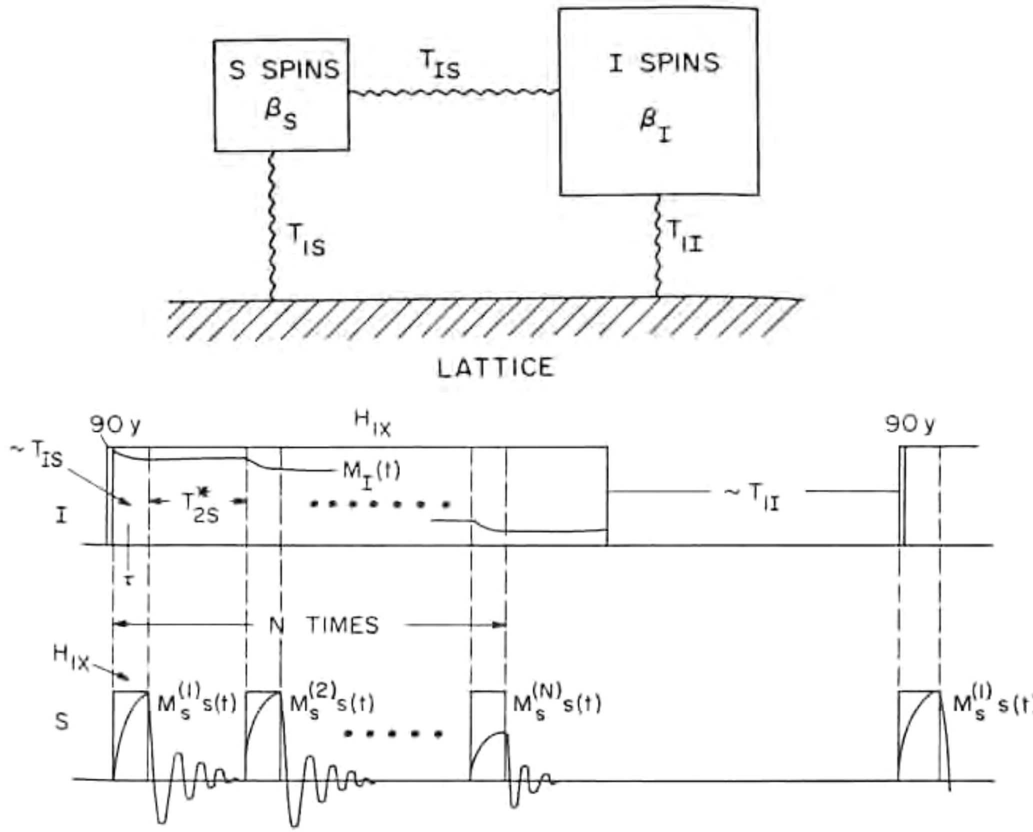
High resolution solid-state NMR spectra of crystals and powders

Proton-Enhanced Nuclear Induction Spectroscopy. A Method for High Resolution NMR of Dilute Spins in Solids*

A. Pines, M. G. Gibby,† and J. S. Waugh

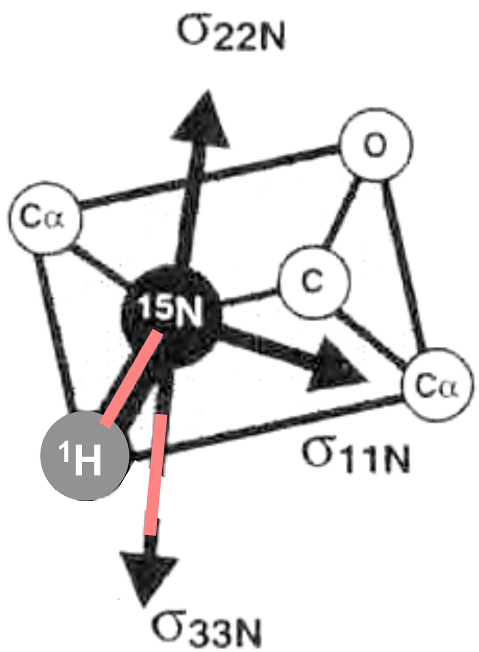
Department of Chemistry and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139



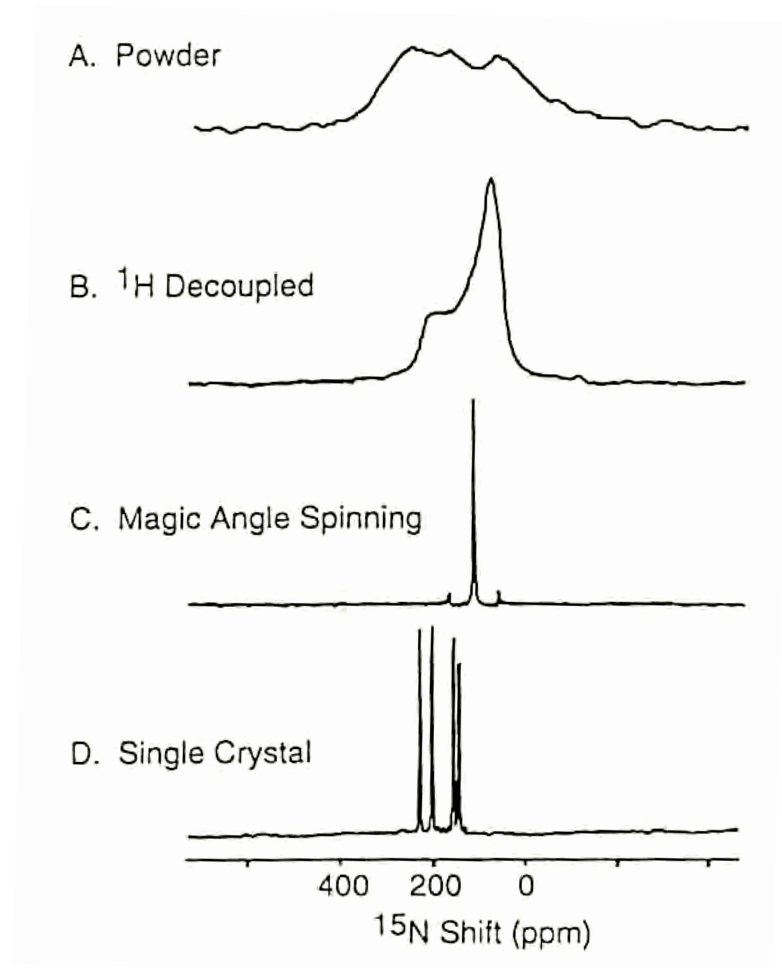


1972

Solid-state ^{15}N NMR spectra of a model peptide crystal.



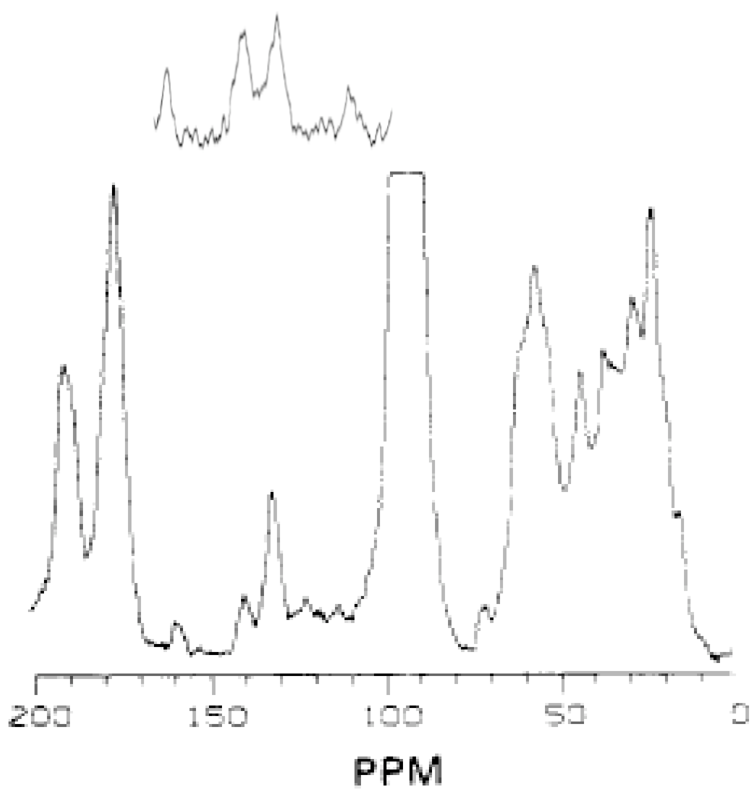
^{15}N chemical shift interaction



^{13}C MAS NMR of proteins.

Detection of Individual Carbon Resonances in Solid Proteins

S. J. Opella,* M. H. Frey, T. A. Cross
Department of Chemistry, University of Pennsylvania, Philadelphia, Pennsylvania 19104

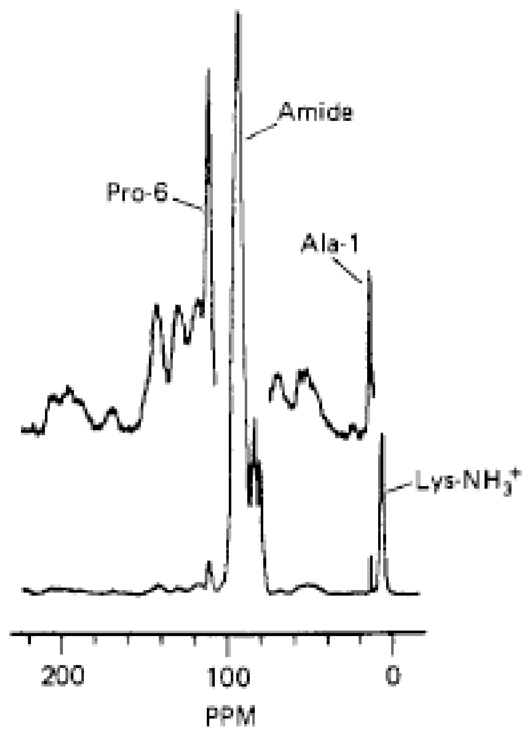


1979

^{15}N MAS NMR of proteins.

Strategy for Nitrogen NMR of Biopolymers

T. A. Cross, J. A. DiVerdi, and S. J. Opella*



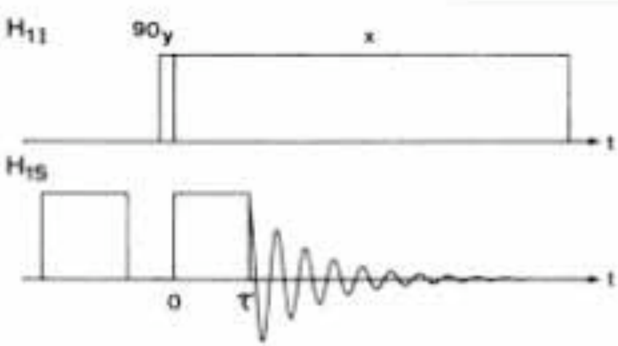
1982

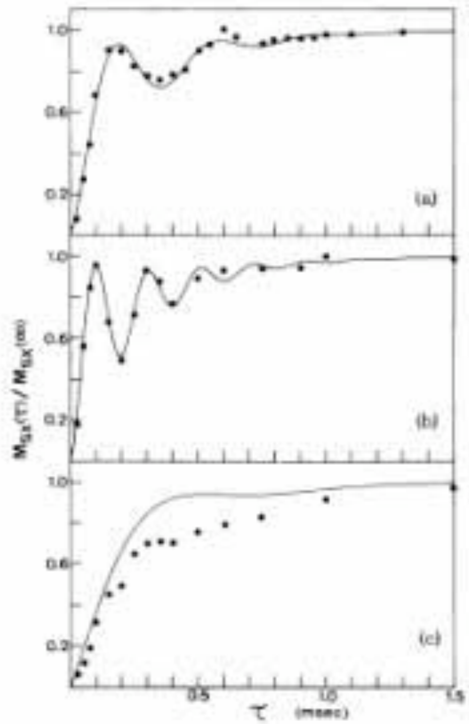
Measurement of dipole-dipole couplings

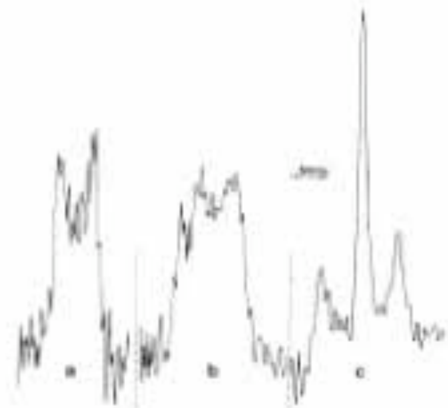
Dipolar oscillations during CP build-up.

Transient Oscillations in NMR Cross-Polarization Experiments in Solids*

Luciano Müller, Anil Kumar, Thomas Baumann, and Richard R. Ernst
Laboratorium für Physikalische Chemie, Eidgenössische Technische Hochschule, 8006 Zürich, Switzerland





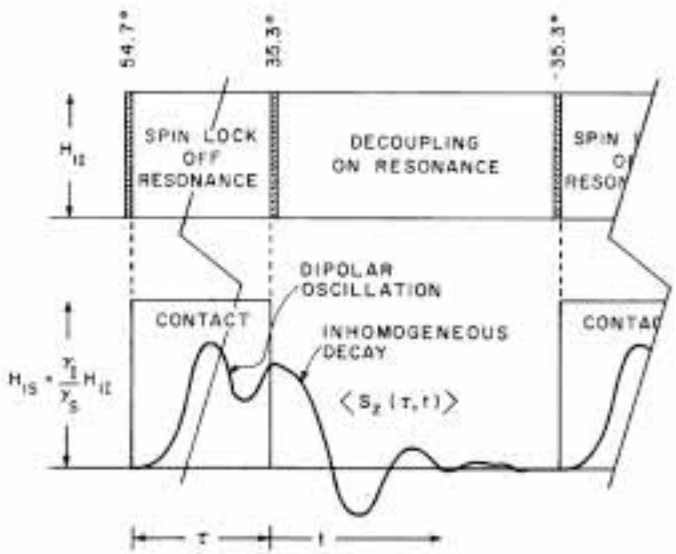


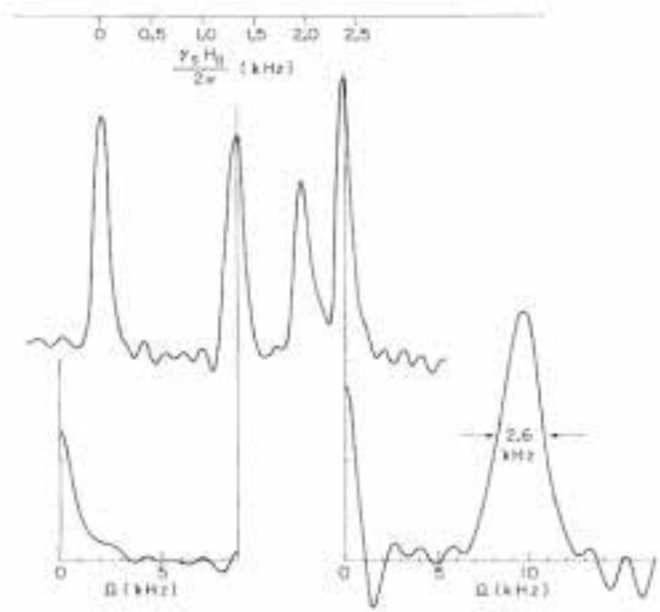
1974

Dipolar oscillations during CP build-up under Lee-Goldburg irradiation and analyzed by Fourier transformation.

Resolved Dipolar Coupling Spectra of Dilute Nuclear Spins in Solids*

R. K. Hester, J. L. Ackerman, V. R. Cross, and J. S. Waugh
Department of Chemistry and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139



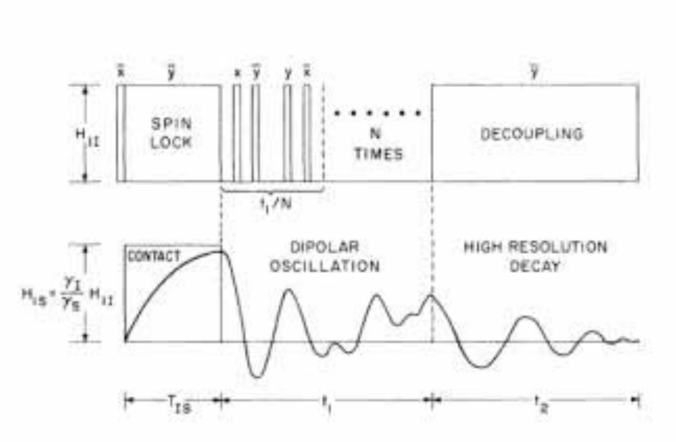


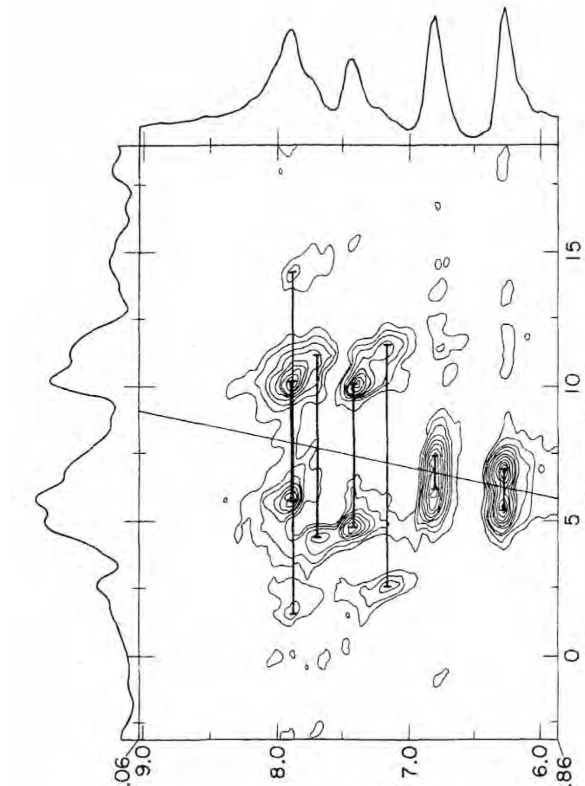
1975

Separated local field spectra of a single crystal.

Separated Local Field Spectra in NMR: Determination of Structure of Solids*

R. K. Hester, J. L. Ackerman, B. L. Neff, and J. S. Waugh
Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 March 1976)





Separation by:

1) **chemical shifts of the dilute spins**
2) **homonuclear decoupling of the abundant spins**

1976

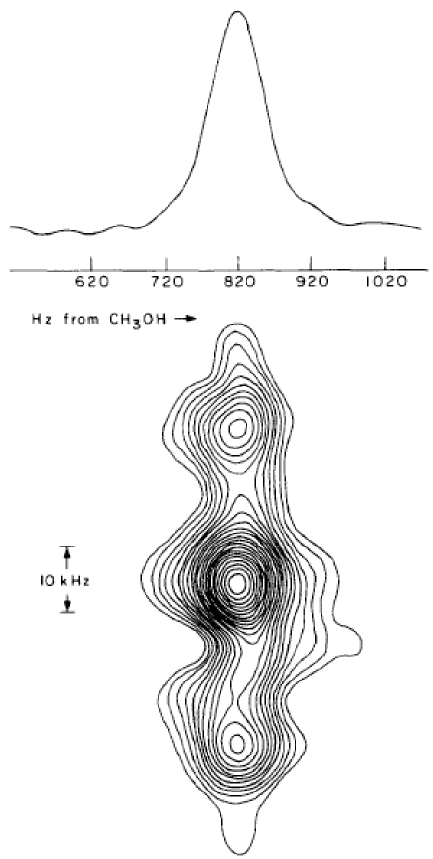
High resolution solid-state NMR spectra of aligned samples

Separated local field spectra of a uniaxially aligned polymer.

Two-dimensional ^{13}C NMR of highly oriented polyethylene*

Stanley J. Opella[†] and J. S. Waugh

Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139



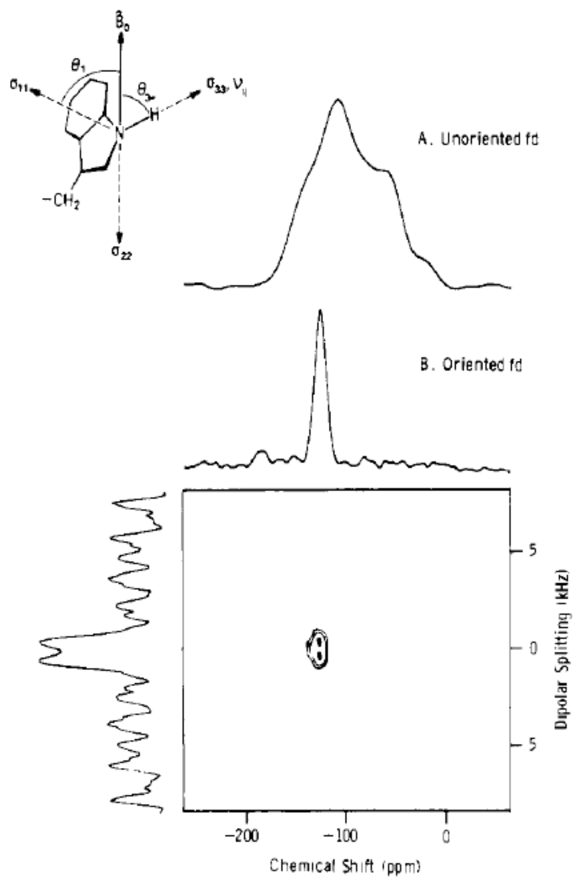
1977

Separated local field spectrum of a specifically ^{15}N labeled protein aligned and immobilized within a virus particle.

Protein Structure by Solid-State NMR

T. A. Cross and S. J. Opella*

Department of Chemistry, University of Pennsylvania
Philadelphia, Pennsylvania 19104



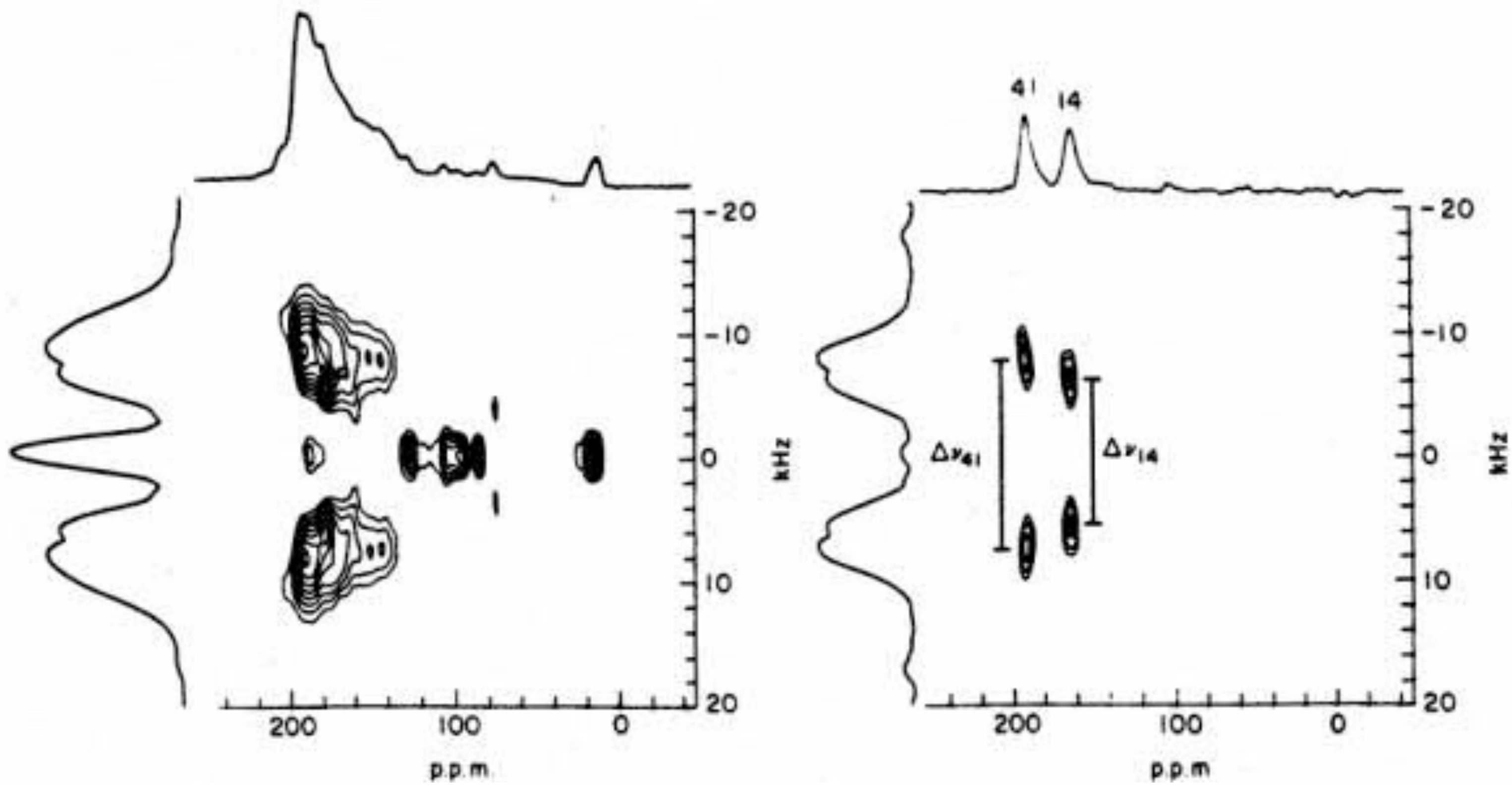
1983

Separated local field spectra of selectively and uniformly ^{15}N proteins aligned and immobilized within a virus particle.

Protein Structure by Solid State Nuclear Magnetic Resonance

Residues 40 to 45 of Bacteriophage fd Coat Protein

T. A. Cross† and S. J. Opella



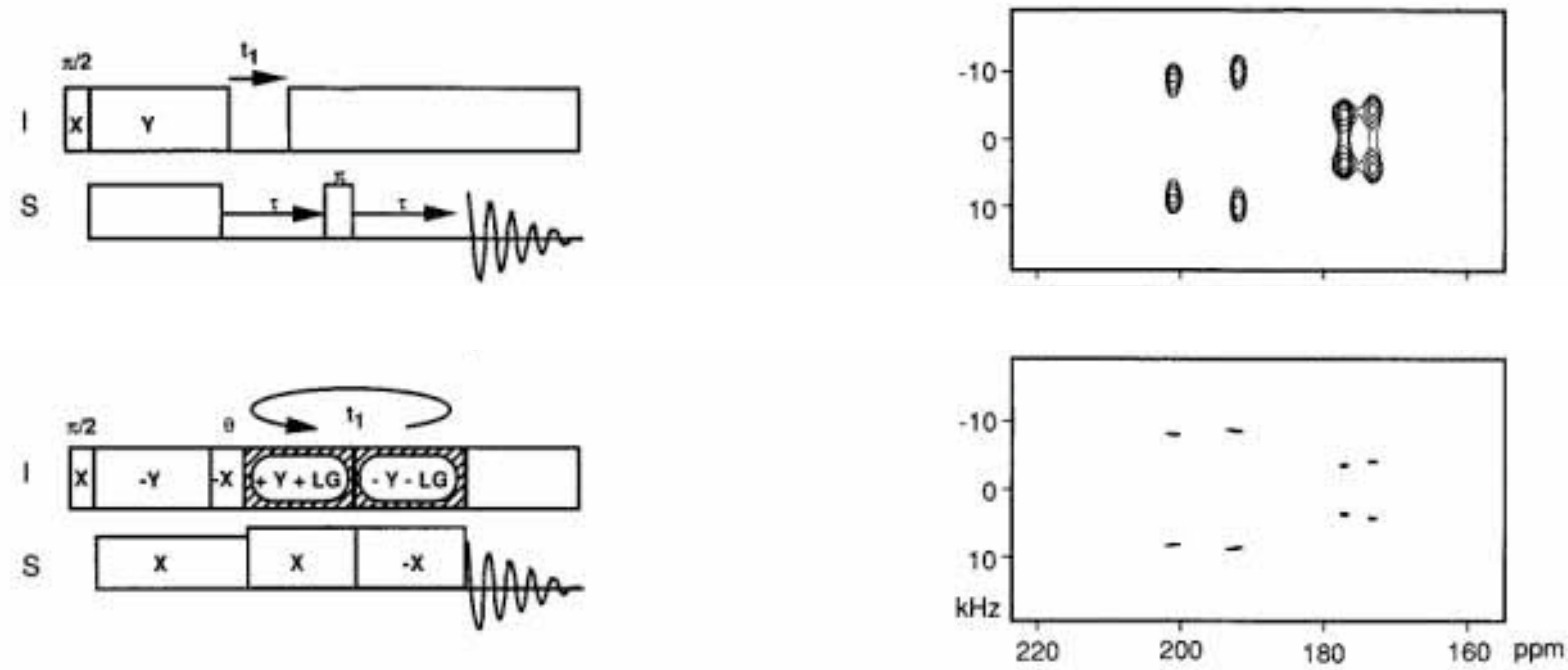
1985

PISEMA

High-Resolution Heteronuclear Dipolar Solid-State NMR Spectroscopy

C. H. WU, A. RAMAMOORTHY, AND S. J. OPELLA

Department of Chemistry, University of Pennsylvania, Philadelphia, Pennsylvania 19104



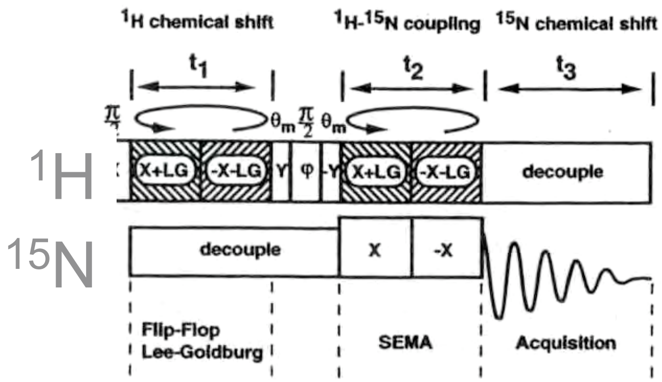
1994

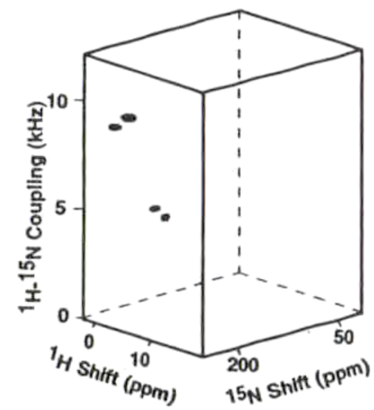
Three-dimensional HETCOR/PISEMA $^{1}H/^{15}N$ experiments.

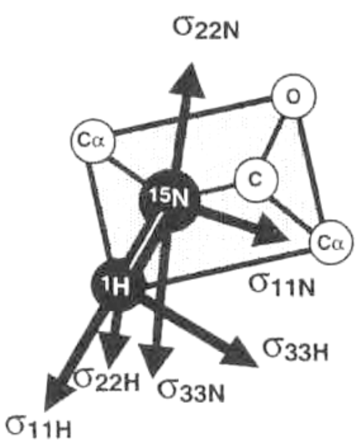
Three-Dimensional Solid-State NMR Experiment That Correlates the Chemical Shift and Dipolar Coupling Frequencies of Two Heteronuclei

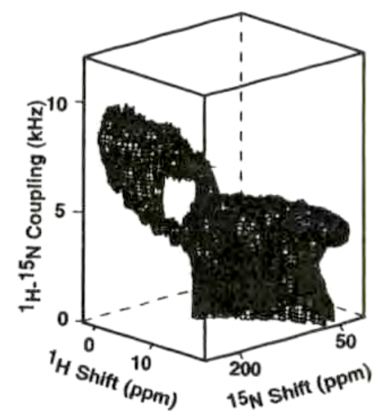
A. RAMAMOORTHY, C. H. WU, AND S. J. OPELLA

Department of Chemistry, University of Pennsylvania, Philadelphia, Pennsylvania 19104







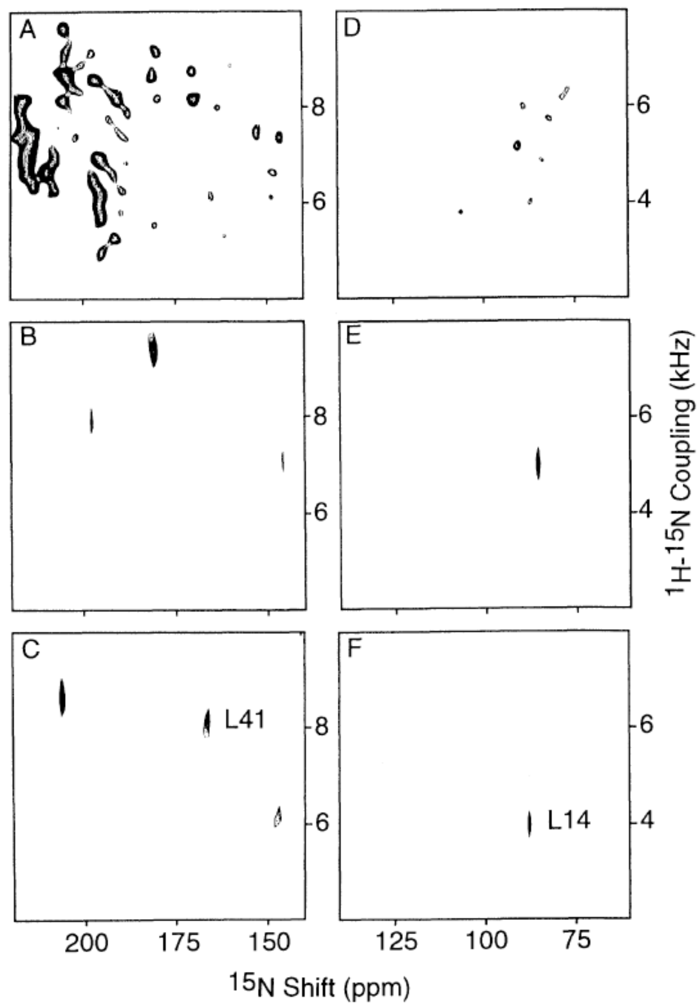


1995

Complete resolution of a uniformly ^{15}N labeled membrane protein.

Complete resolution of the solid-state NMR spectrum of a uniformly ^{15}N-labeled membrane protein in phospholipid bilayers

FRANCESCA M. MARASSI, A. RAMAMOORTHY*, AND STANLEY J. OPELLA†



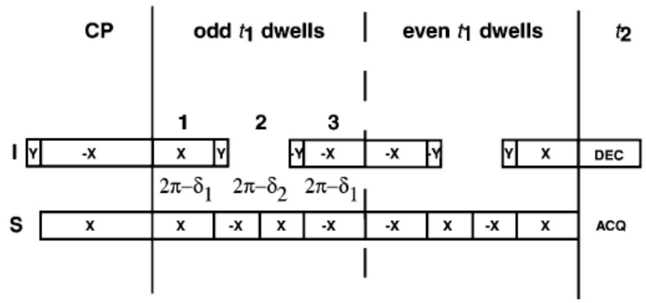
1997

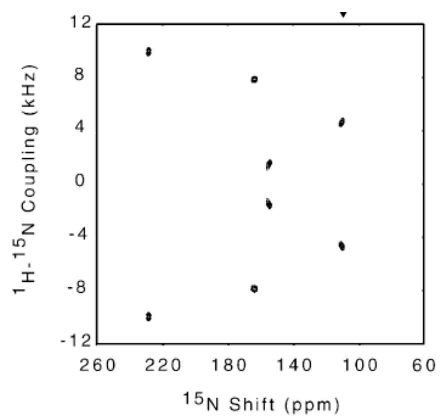
SAMMY.

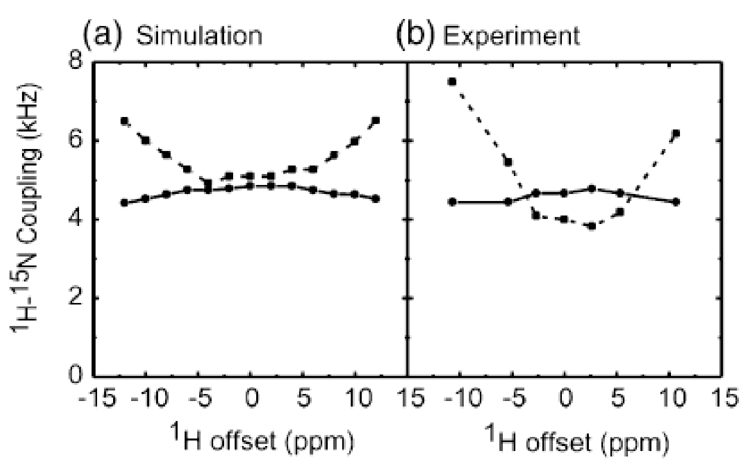
A "Magic Sandwich" pulse sequence with reduced offset dependence for high-resolution separated local field spectroscopy

Alexander A. Nevzorov and Stanley J. Opella*

Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, CA 92093-0307, USA



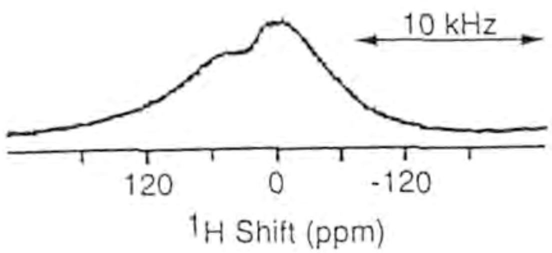




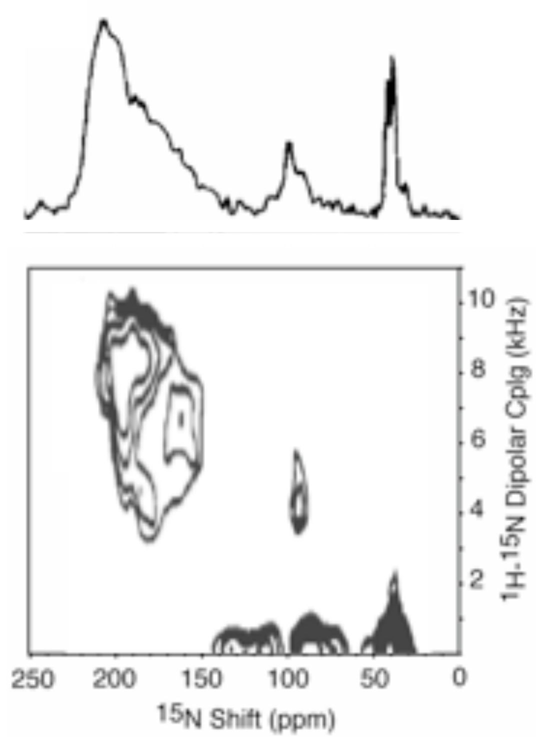
2003

Improvements in solid-state NMR spectra of proteins.

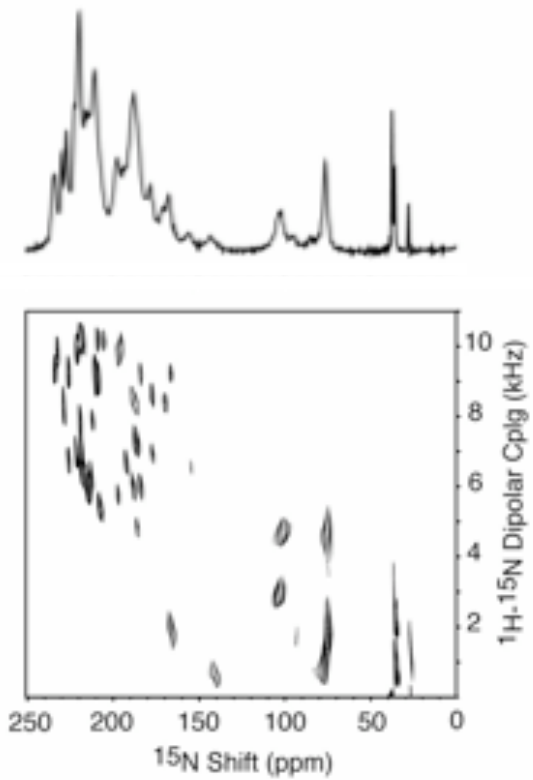
1976



1983

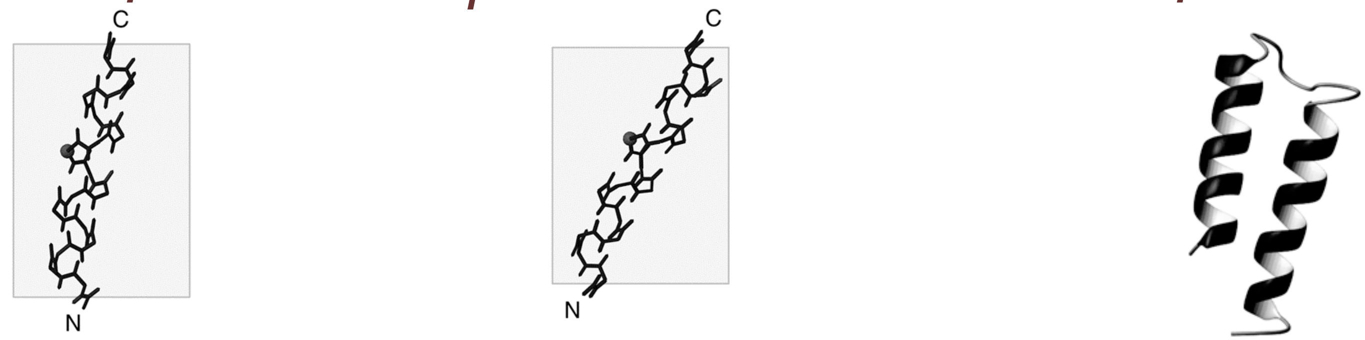


2004



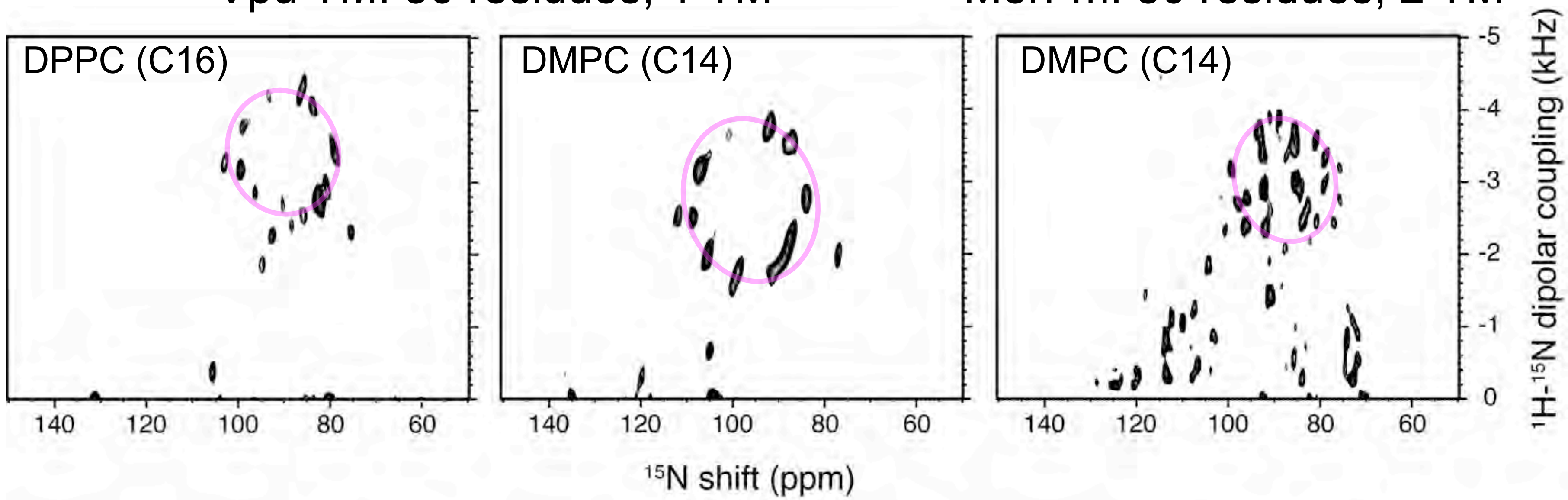
Mapping of structure onto spectra.

In aligned samples, orientationally dependent resonance frequencies map the structure onto the spectra.



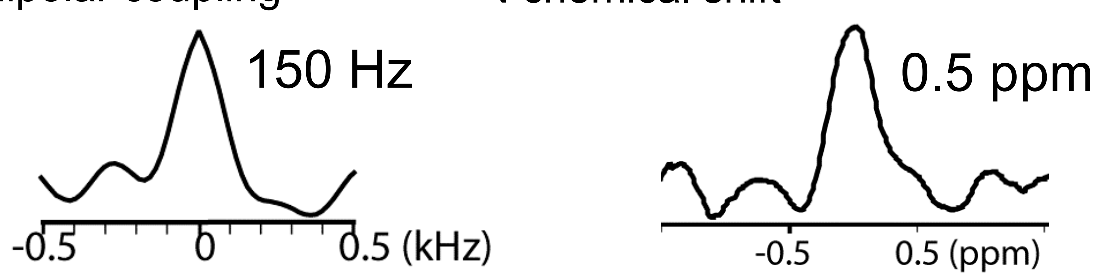
Vpu TM: 36 residues, 1 TM

MerFm: 80 residues, 2 TM



^{1}H-^{15}N dipolar coupling

^{15}N chemical shift



PISA Wheels: Polarity Index Slant Angle.

A Solid-State NMR Index of Helical Membrane Protein Structure and Topology

Francesca M. Marassi* and Stanley J. Opella†

**The Wistar Institute, Philadelphia, Pennsylvania 19104-4268; and †Department of Chemistry, University of Pennsylvania, Philadelphia, Pennsylvania 19014-6323*

Imaging Membrane Protein Helical Wheels

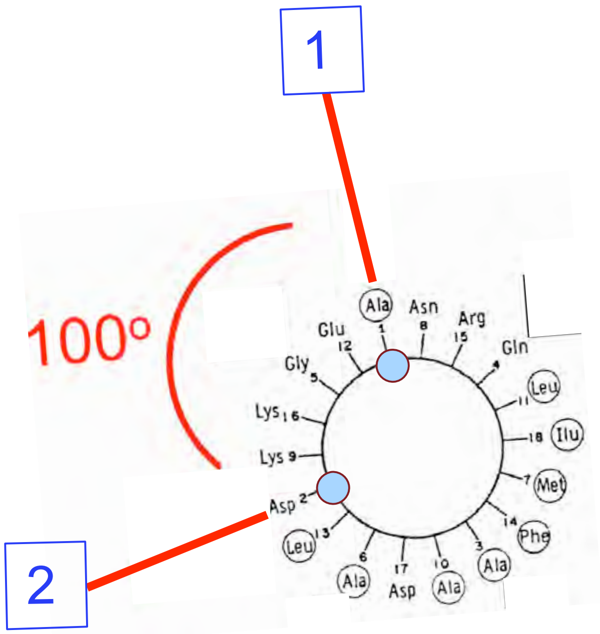
J. Wang,* J. Denny,† C. Tian,* S. Kim,* Y. Mo,‡ F. Kovacs,* Z. Song,§ K. Nishimura,§ Z. Gan,§ R. Fu,§ J. R. Quine,†,§ and T. A. Cross,*,‡,§

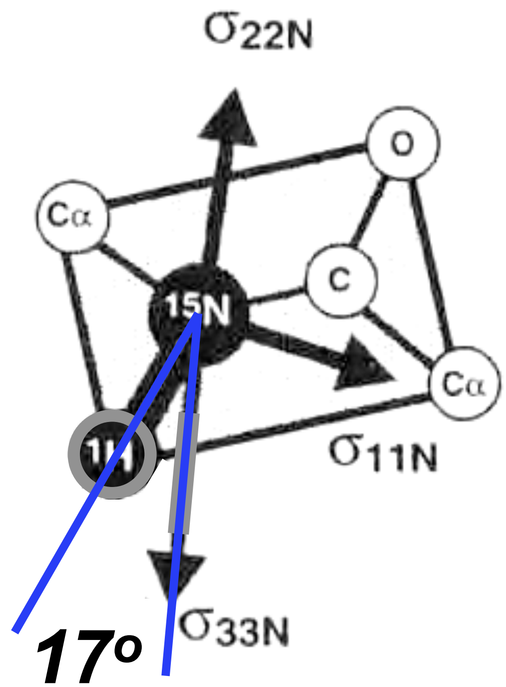
*§National High Magnetic Field Laboratory, *Institute of Molecular Biophysics, †Department of Mathematics, and ‡Department of Chemistry, Florida State University, Tallahassee, Florida 32310*

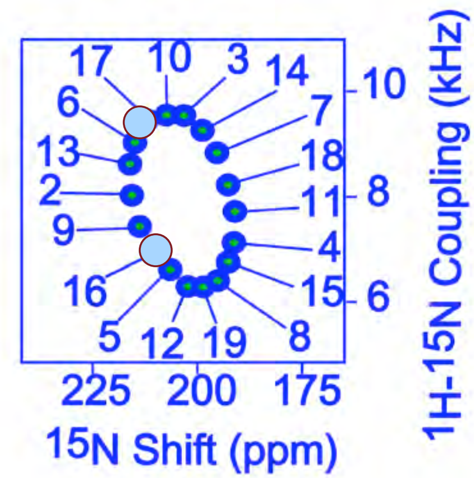
2000

PISA Wheels.

Helical Wheel spin-interactions PISA Wheel





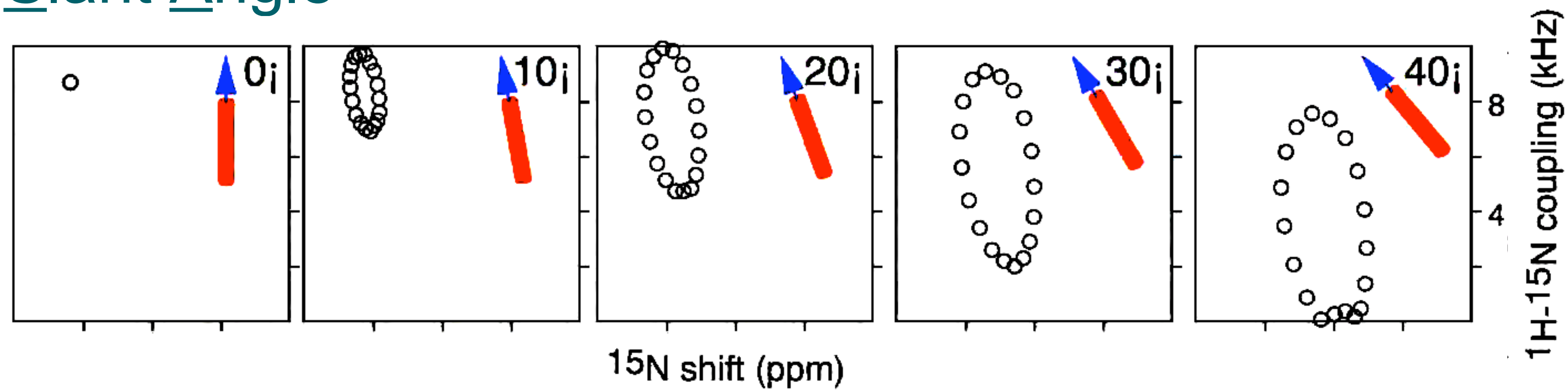


- Projection down helix axis.
- 3.6 residues per turn.
- Arc of 100° between adjacent residues.
- 18 possible orientations.

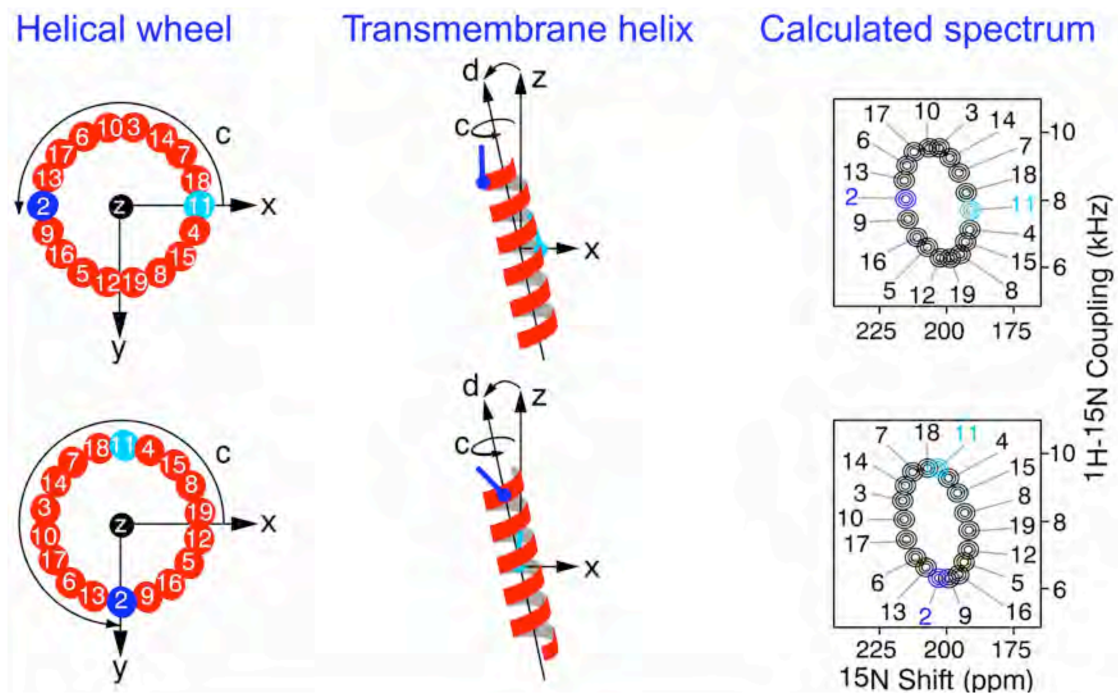
- "wheel-like" spectrum.
- Slant angle (tilt).
- Polarity index (rotation).
- 18 possible resonances

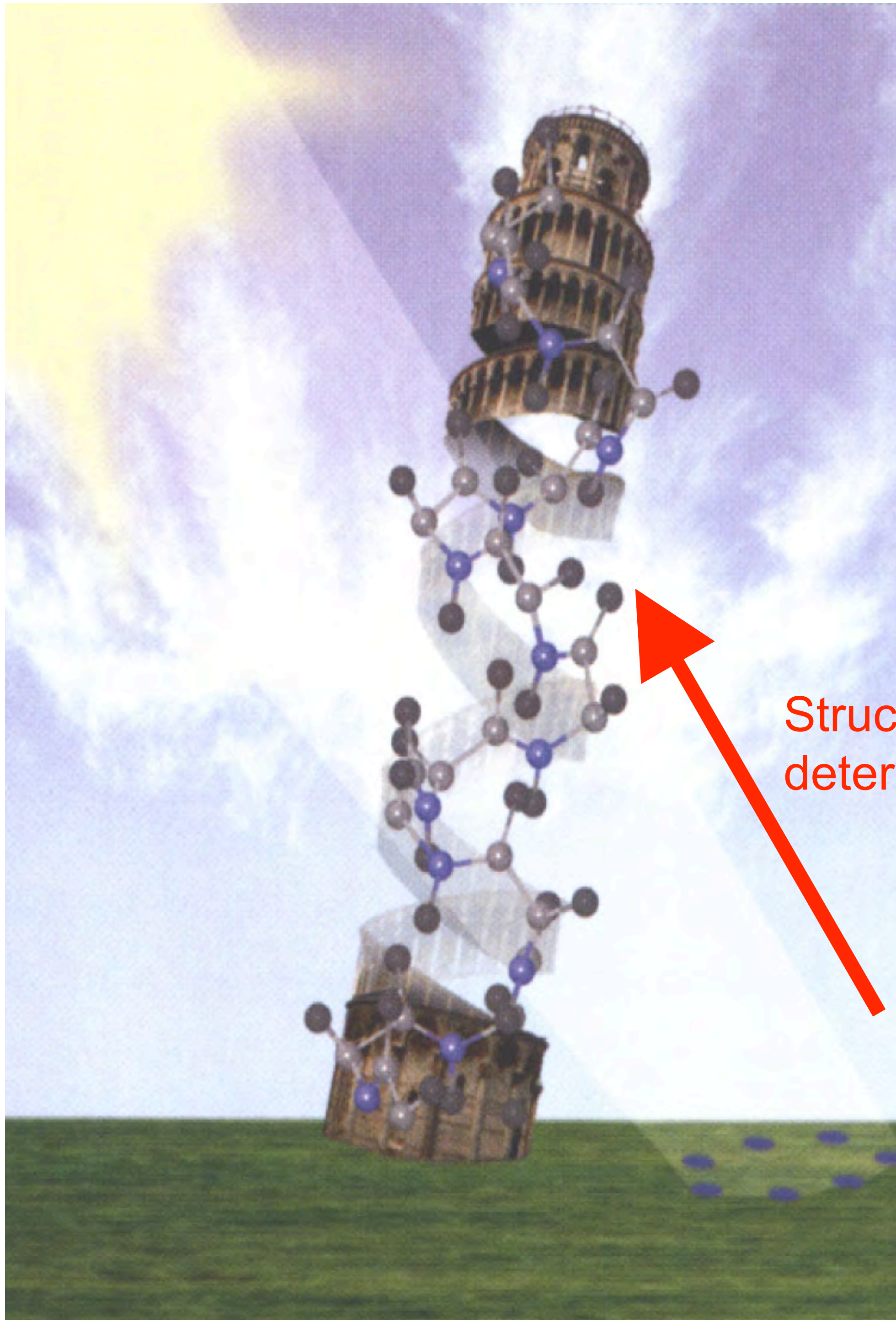
PISA wheels.

Slant Angle



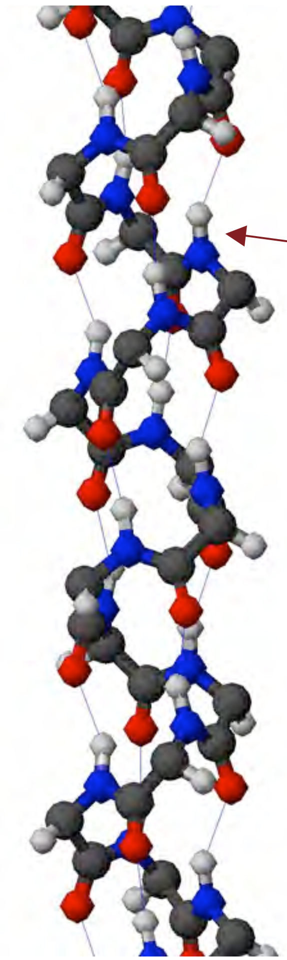
Polarity Index





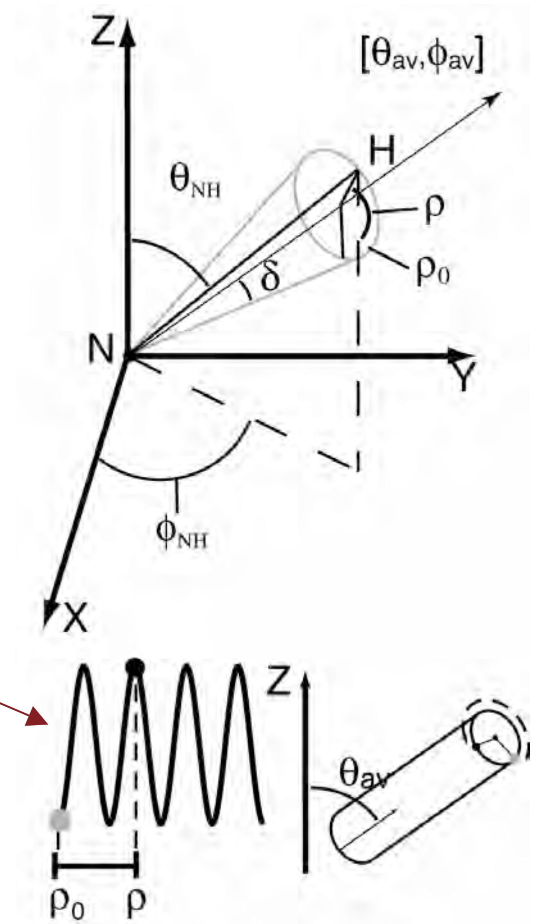
Structure
determination

α-Helix geometry and periodicity.



H-N bond is 15° tilted away from the helix axis

$f(\theta_{av},\phi_{av},\rho_0)$



Periodicity in α-helical secondary structure.

Helix Tilt of the M2 Transmembrane Peptide from Influenza A Virus: An Intrinsic Property

F. A. Kovacs[1,2], Jeffrey K. Denny[1,3], Z. Song[1], J. R. Quine[1] and T. A. Cross[1,2,4*]

2000

Dipolar Waves as NMR Maps of Protein Structure

Michael F.Mesleh,[†] Gianluigi Veglia,[‡] Tara M. DeSilva,[§] Francesca M. Marassi,[||] and Stanley J. Opella[*,†]

Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, California 92093, Department of Chemistry, University of Minnesota, Minneapolis, Minnesota 53485, and The Burnham Institute, 10901 North Torrey Pines Road, La Jolla, California 92037

Received December 21, 2001

2002

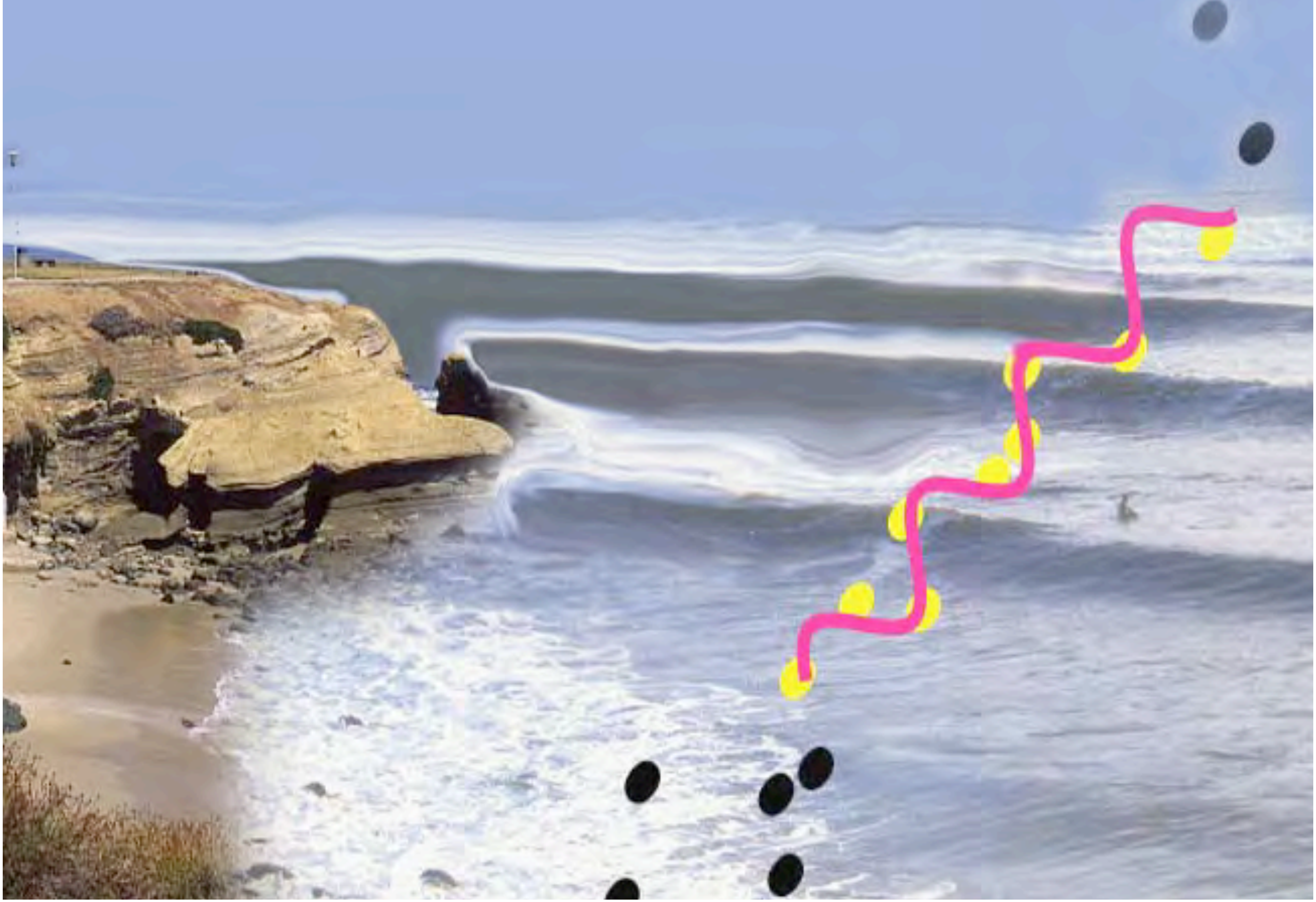
Dipolar Waves Map the Structure and Topology of Helices in Membrane Proteins

Michael F. Mesleh,[†] Sangwon Lee,[†] Gianluigi Veglia,[‡] David S. Thiriot,[†] Francesca M. Marassi,[§] and Stanley J. Opella[*,†]

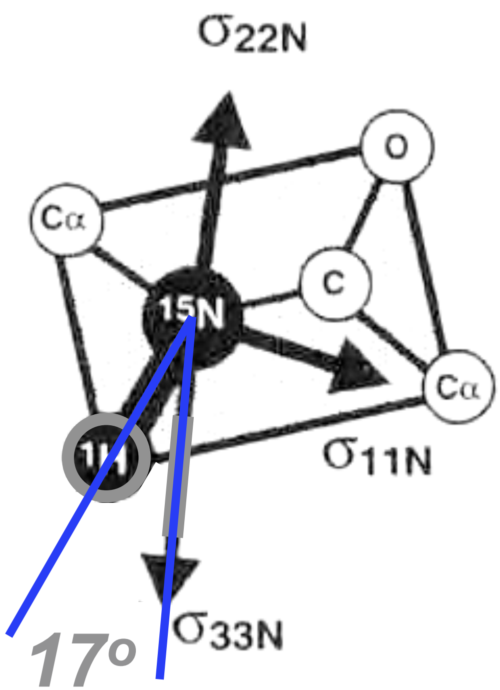
Contribution from the Department of Chemistry and Biochemistry, University of California, San Diego, 9500 Gilman Drive La Jolla, California 92093, Department of Chemistry, University of Minnesota, Minneapolis, 207 Pleasant Street, Minnesota 53485, and The Burnham Institute, 10901 North Torrey Pines Road, La Jolla, California 92037

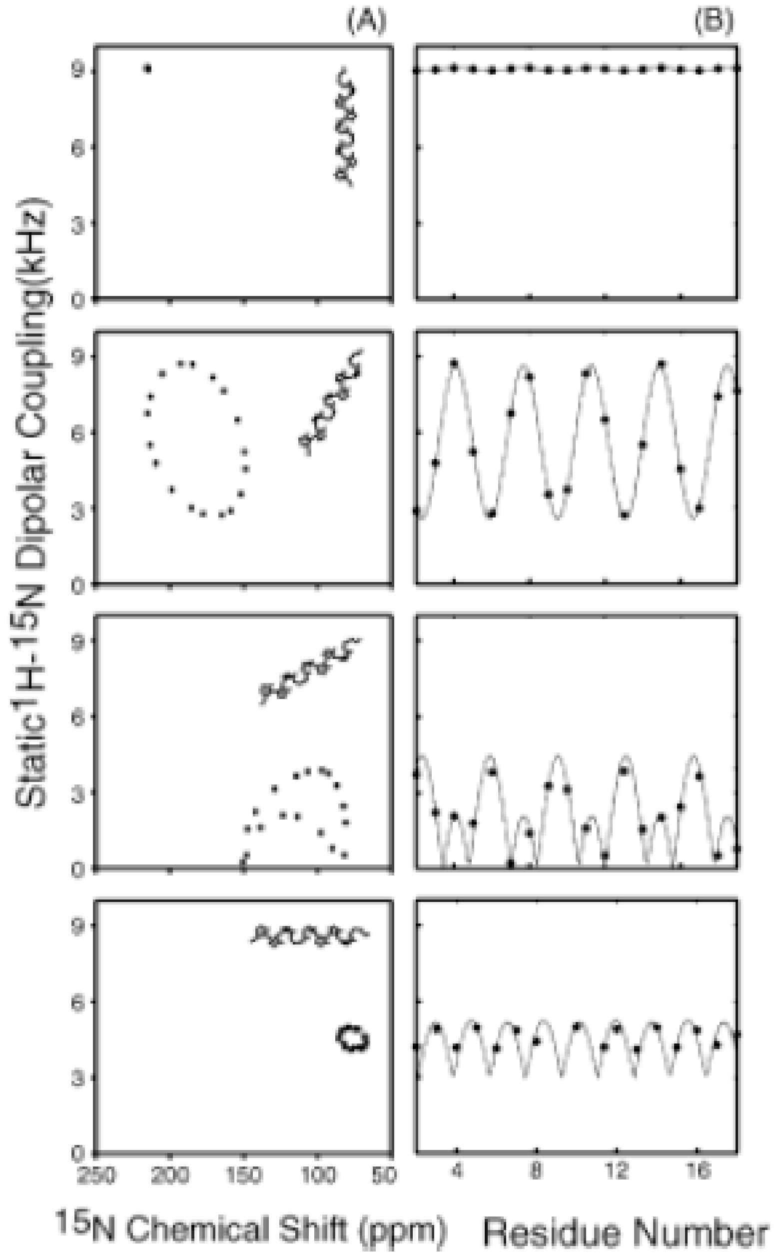
2003

Dipolar Waves: La Jolla Cove.

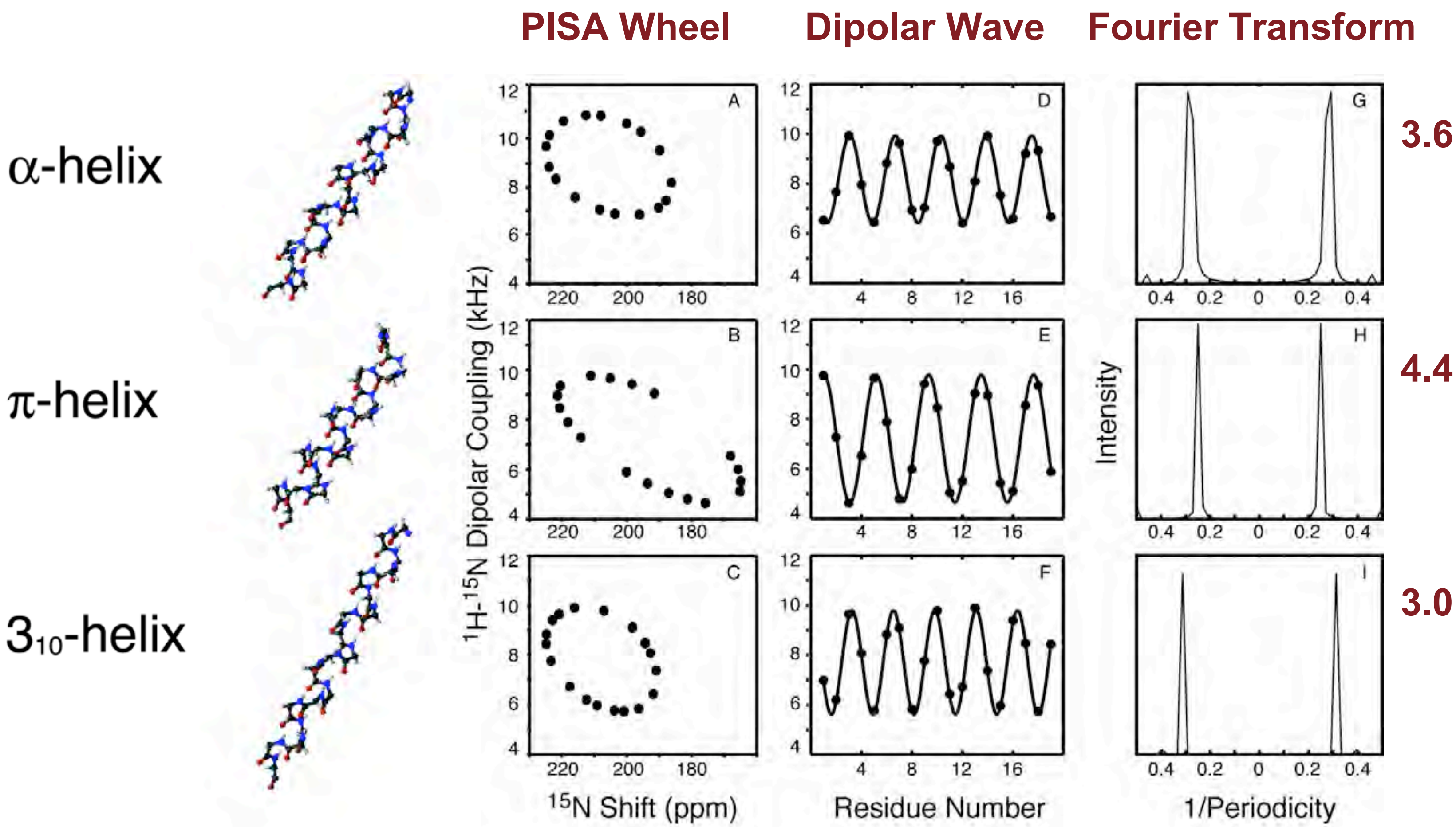


PISA Wheels and Dipolar Waves.

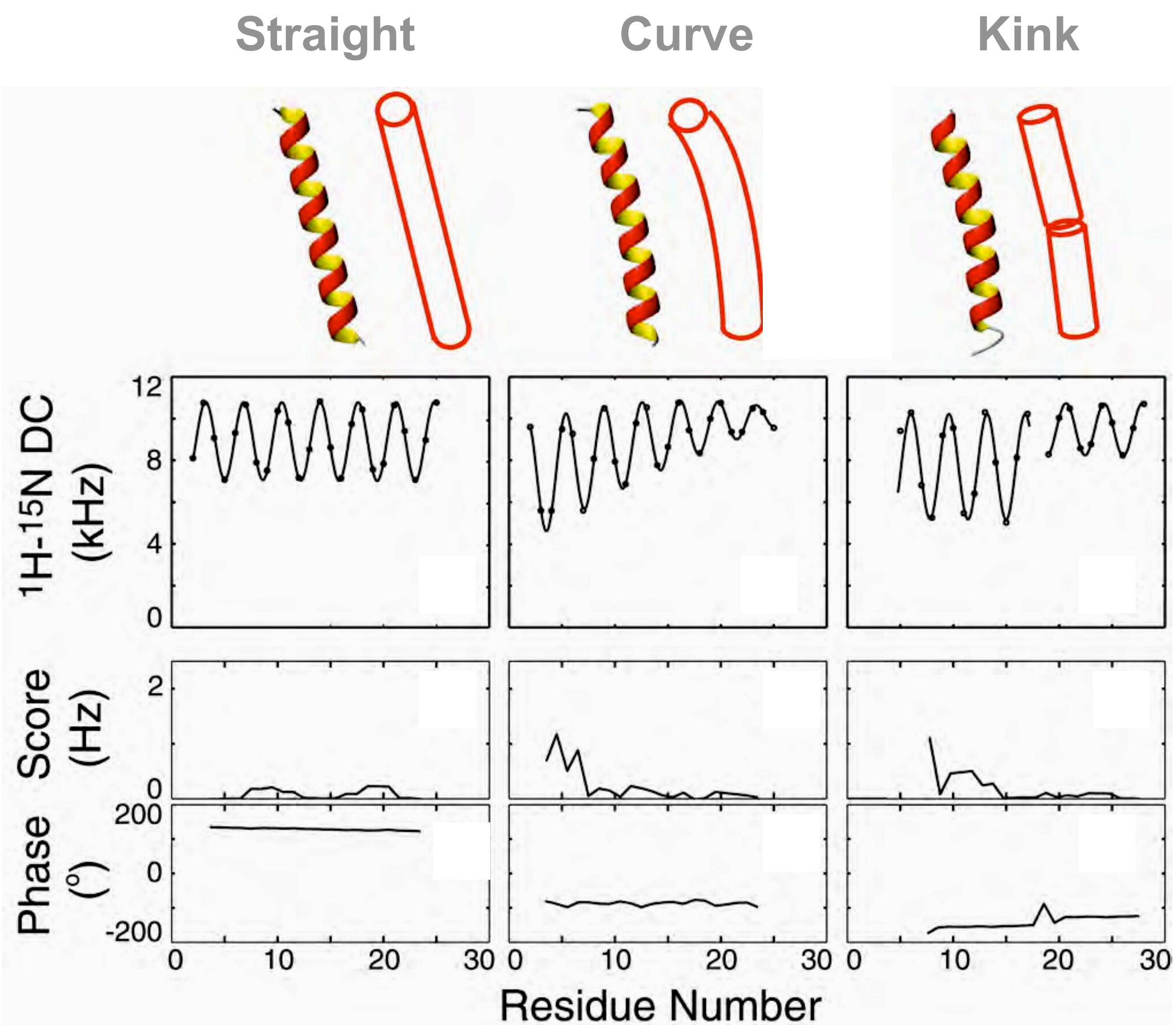




Distinguishing among types of helices.

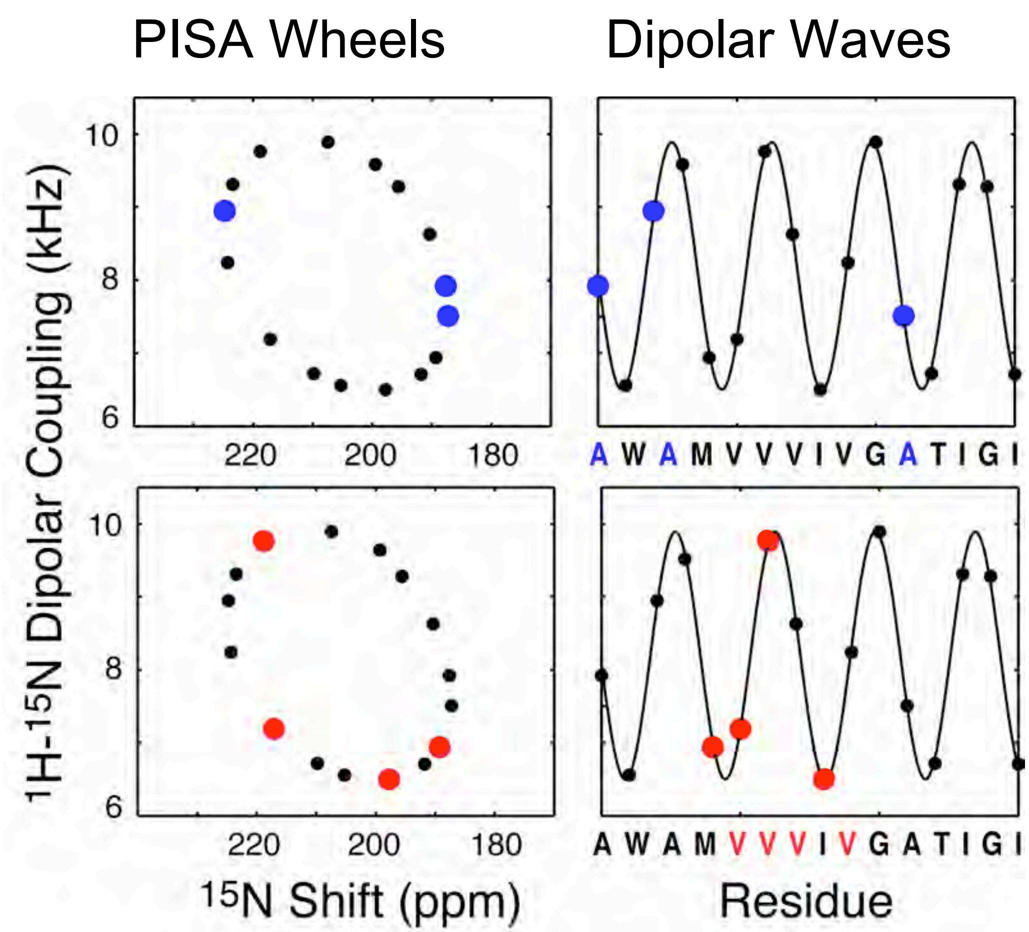


Dipolar Waves: helix distortions.



Wheels, Waves and resonance assignments.

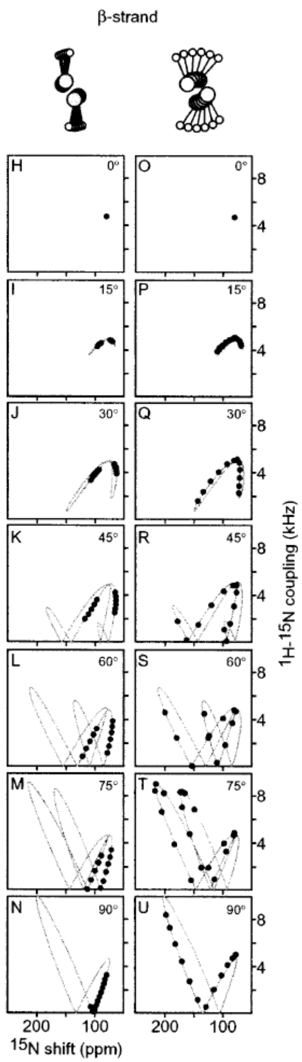
"Shotgun" effect of selective isotopic labeling by residue type.

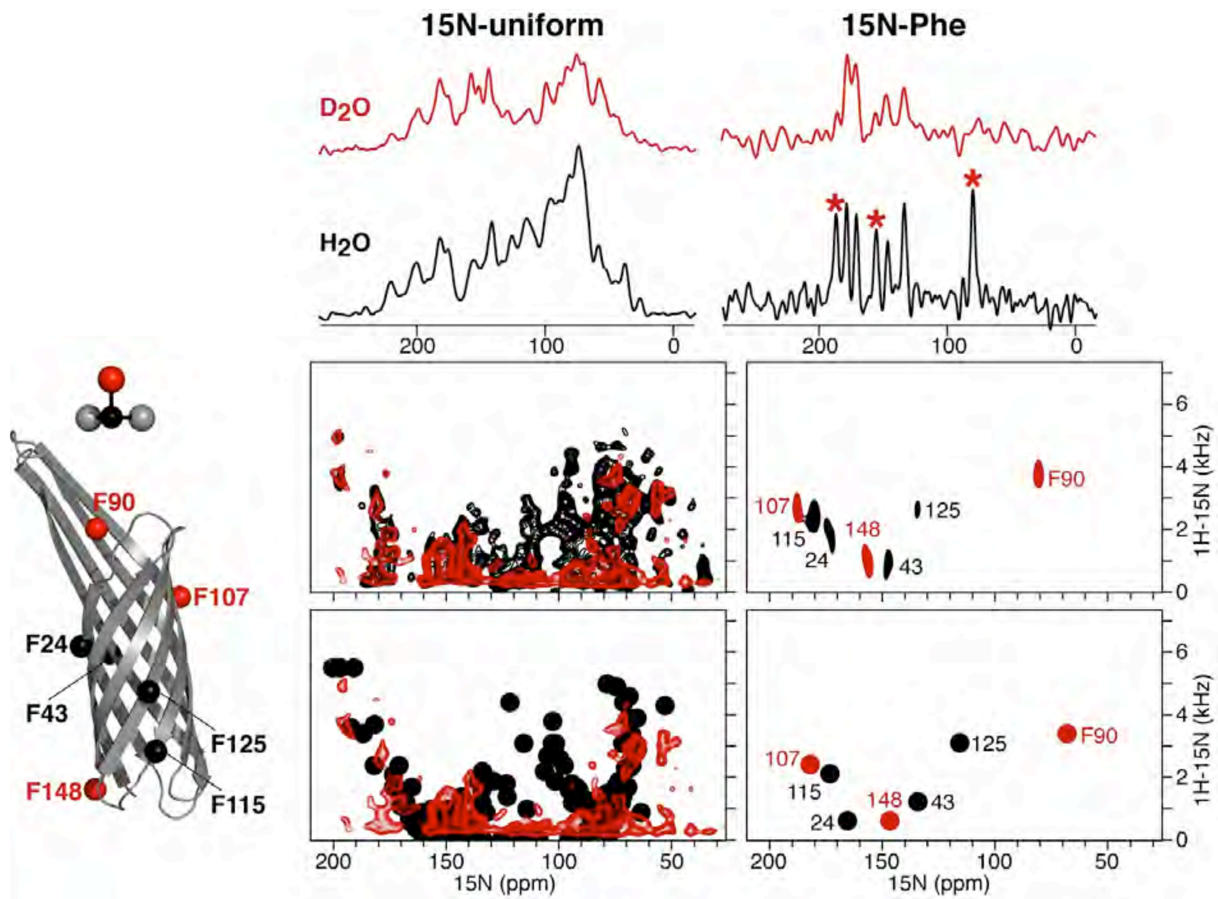


Periodicity in β-sheet secondary structure.

A Simple Approach to Membrane Protein Secondary Structure and Topology based on NMR Spectroscopy

Francesca M. Marassi
The Wistar Institute, Philadelphia, Pennsylvania 19104 USA





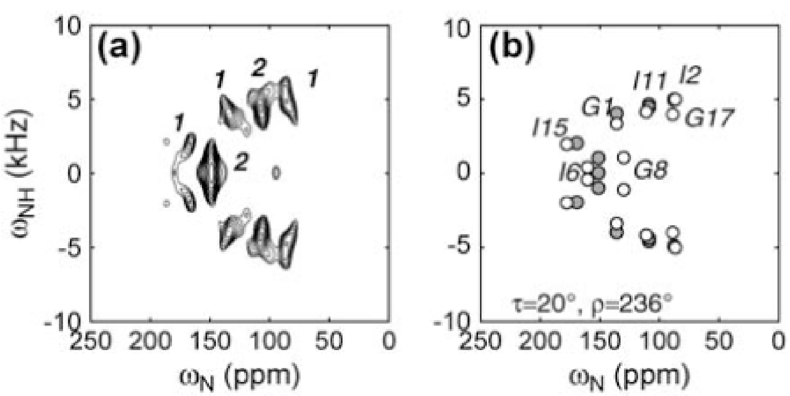
Maha Radhakrihnan and Francesca Marassi

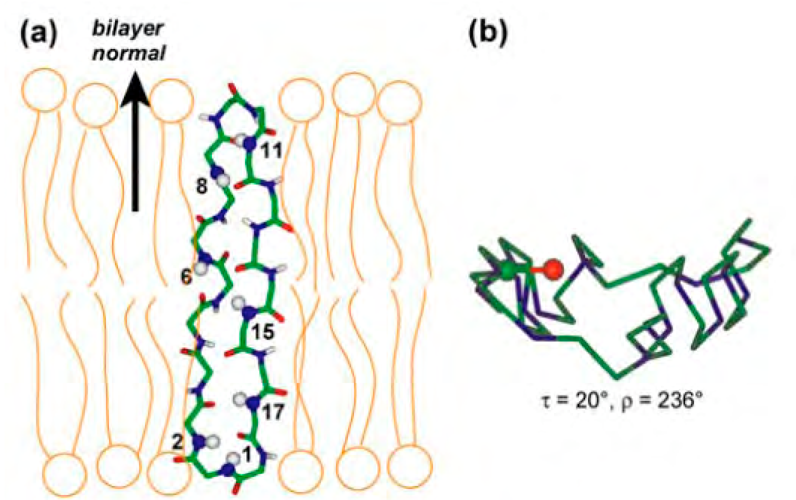
2001

Orientation of β-sheet peptides in membranes through their "butterfly" patterns.

Orientation of a β-Hairpin Antimicrobial Peptide in Lipid Bilayers from Two-Dimensional Dipolar Chemical-Shift Correlation NMR

Ming Tang,* Alan J. Waring,† Robert I. Lehrer,† and Mei Hong*
*Department of Chemistry, Iowa State University, Ames, Iowa 50011; and †Department of Medicine, University of California at Los Angeles School of Medicine, Los Angeles, California 90095

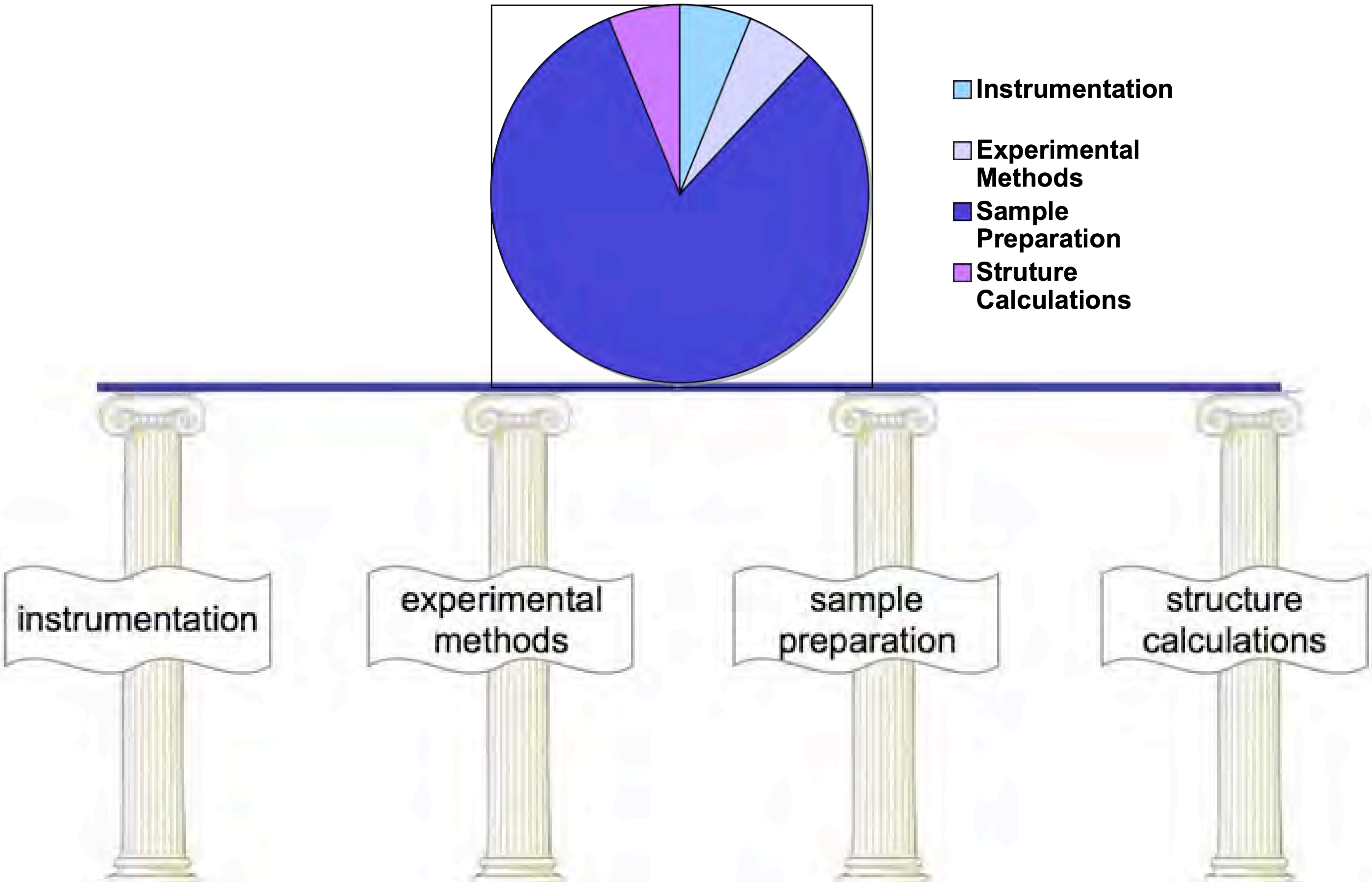




2006

Approach to structure determination.

Relative effort devoted to the four pillars of the Resource.

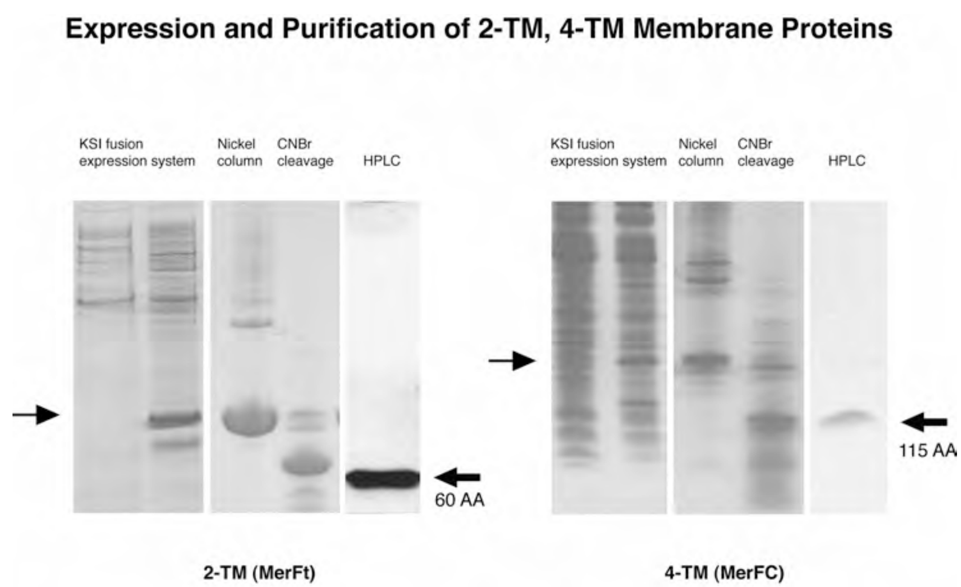


Protein expression and purification.

[14] NMR Experiments on Aligned Samples of Membrane Proteins

By A. A. De Angelis, D. H. Jones, C. V. Grant, S. H. Park, M. F. Mesleh, and S. J. Opella

1) Construct of gene fused to that of a hydrophobic protein (e.g. KSI).
2) Expression in E. coli as inclusion bodies.
3) Use Nickel column to purify fusion protein.
4) Cleave protein from partner using cyanogen bromide.
5) Use HPLC to purify protein.



Wu Sung Son

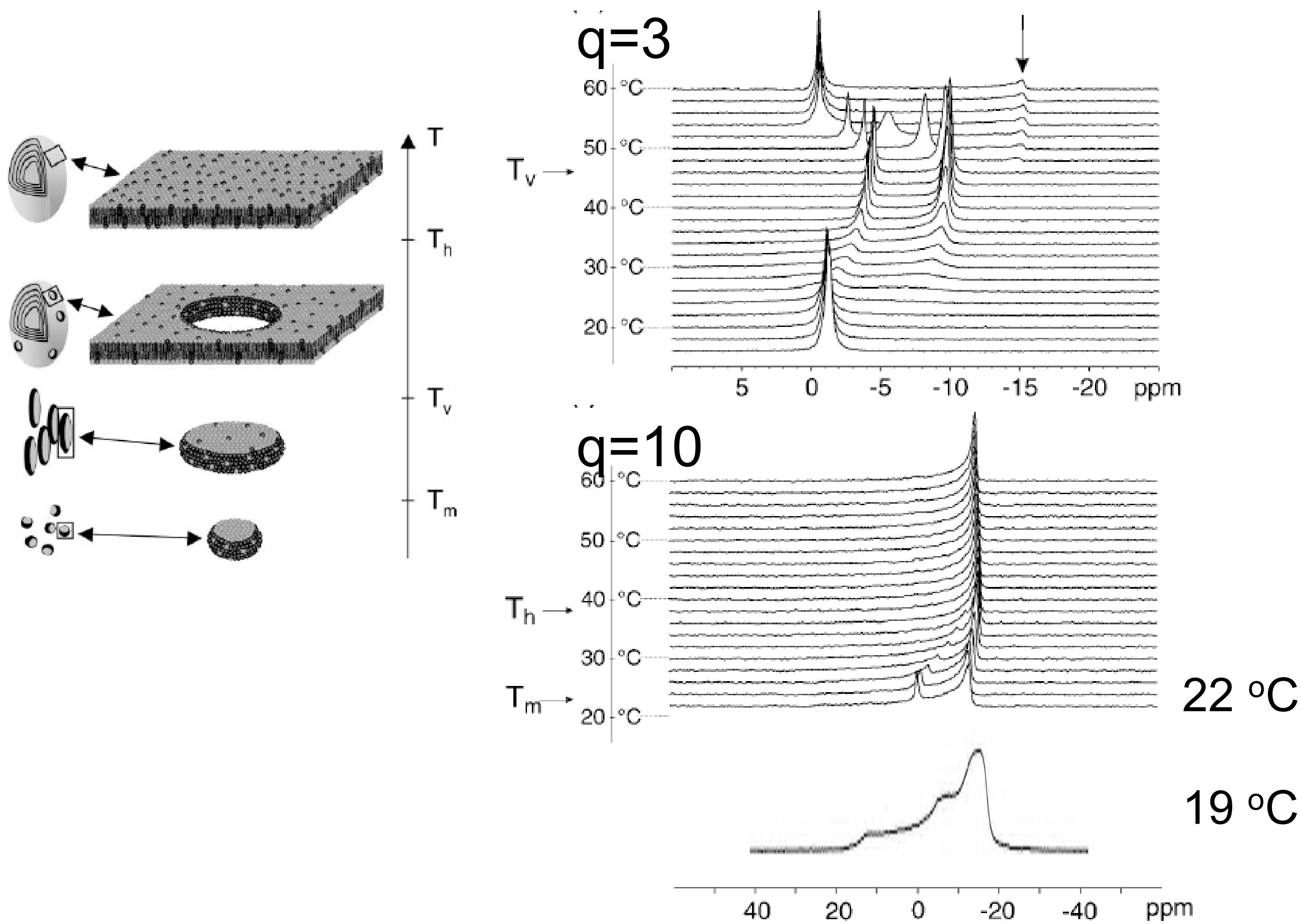
2005

Samples of membrane proteins in lipids.

- Micelles
  - Isotropic
  - Weakly aligned
- Isotropic bicelles
  - $q<0.5$
  - $q=0.5 - 1.0$
- Magnetically aligned bicelles
  - $q=3.2$
  - $q=10$
  - perpendicular
  - parallel
- Bilayers
  - Mechanically aligned on glass plates
  - Static in unoriented samples
  - Rotationally aligned in unoriented samples

Reinvestigation by Phosphorus NMR of Lipid Distribution in Bicelles

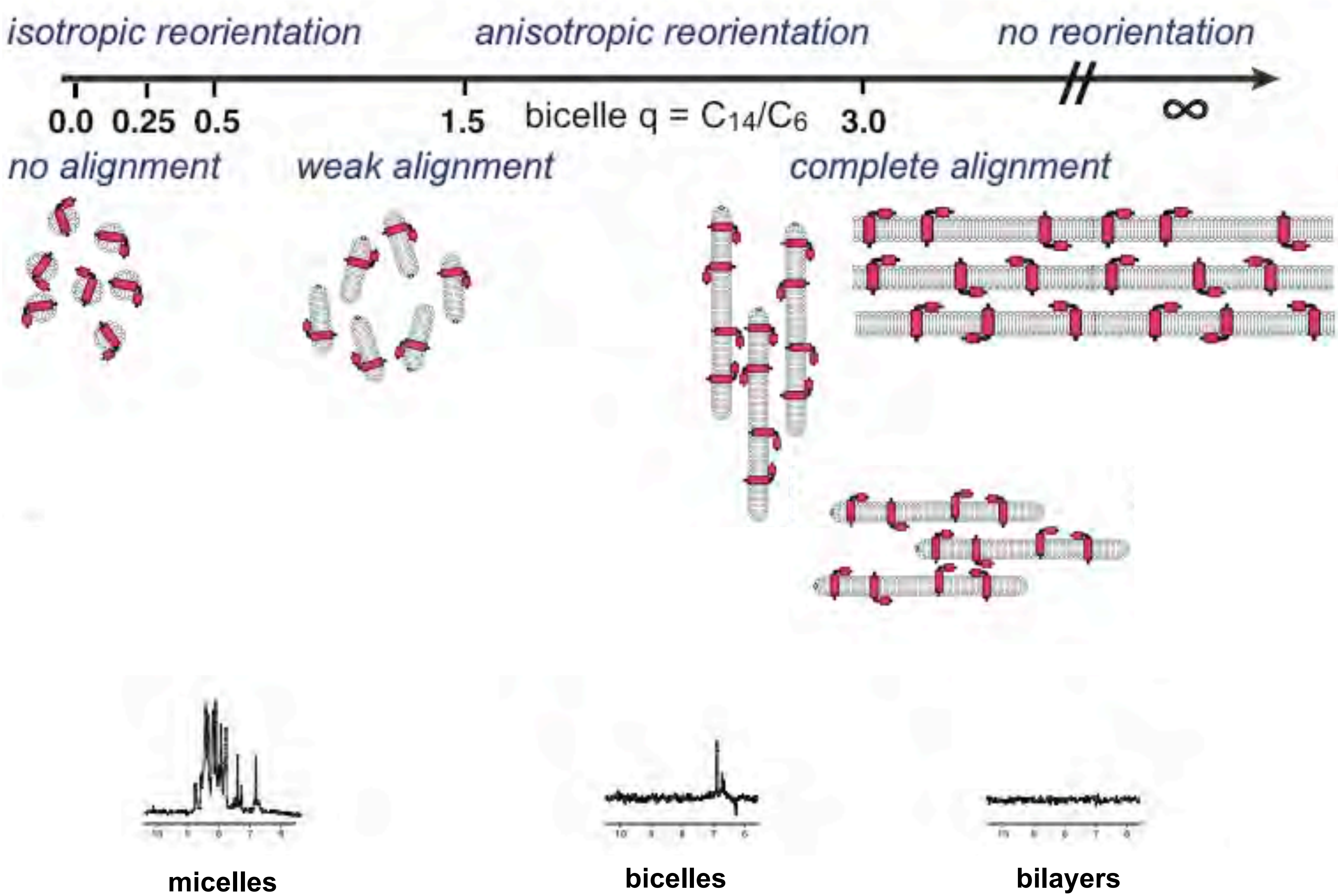
Mohamed N. Triba, Dror E. Warschawski, and Philippe F. Devaux
Unité Mixte de Recherche No. 7099, Centre National de la Recherche Scientifique, Institut de Biologie Physico-Chimique, Paris, France



David Black

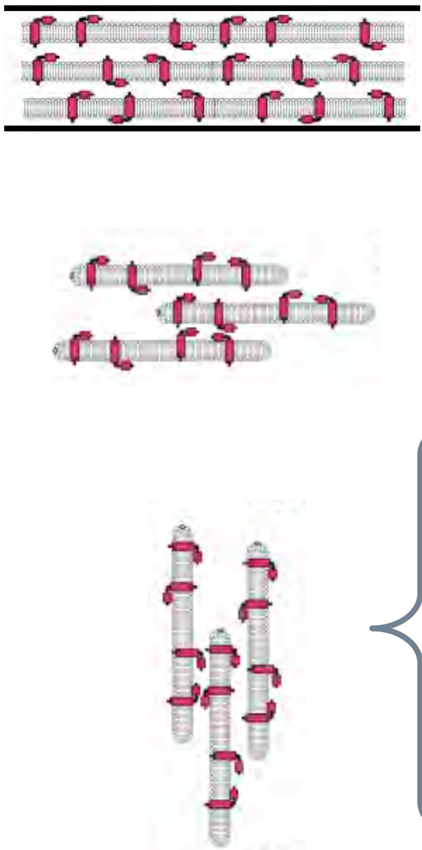
2005

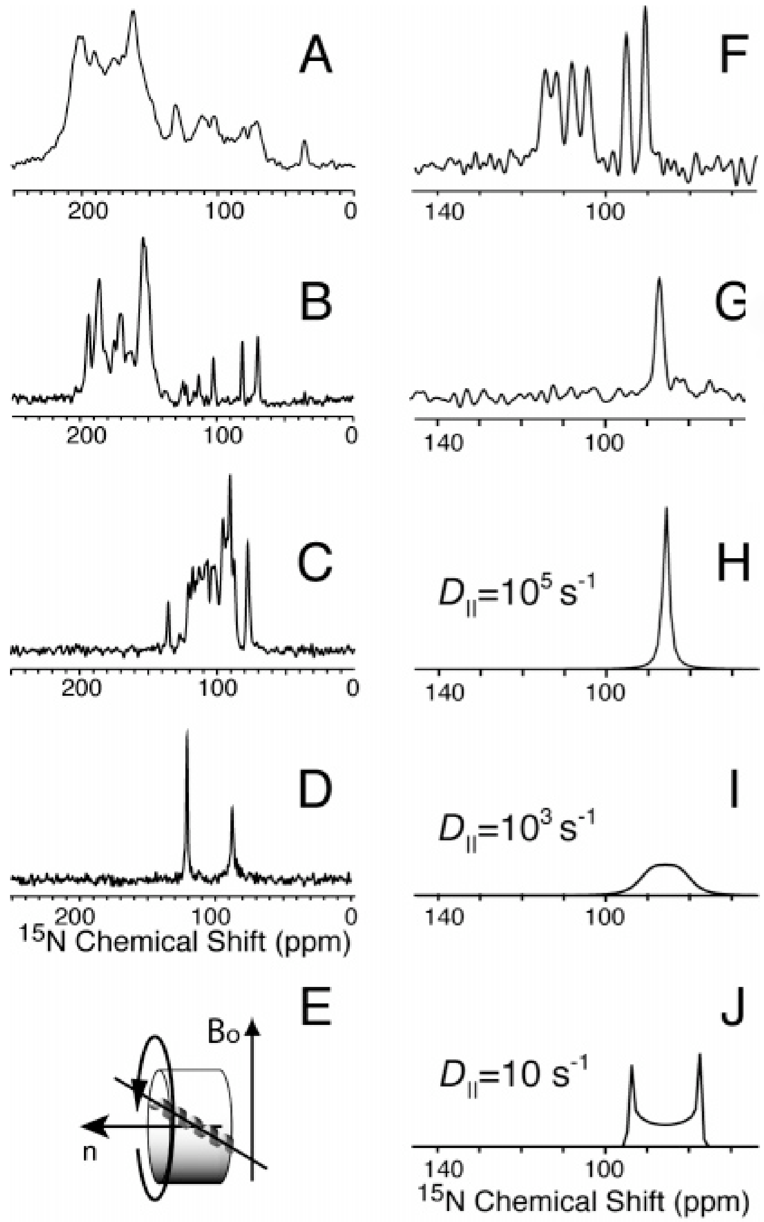
The effects of lipid assemblies on protein reorientation rates.

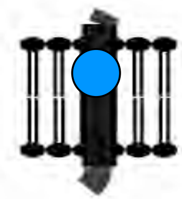


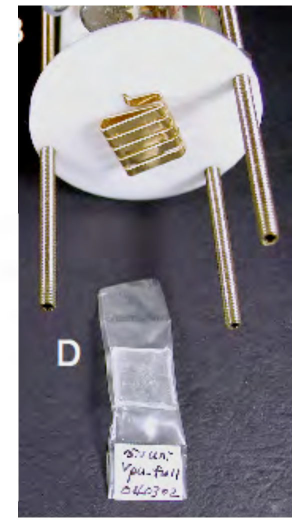
High-Resolution NMR Spectroscopy of Membrane Proteins in Aligned Bicelles

Anna A. De Angelis, Alexander A. Nevzorov, Sang Ho Park, Stanley C. Howell,
Anthony A. Mrse, and Stanley J. Opella*









2004

Motional averaging of powder patterns

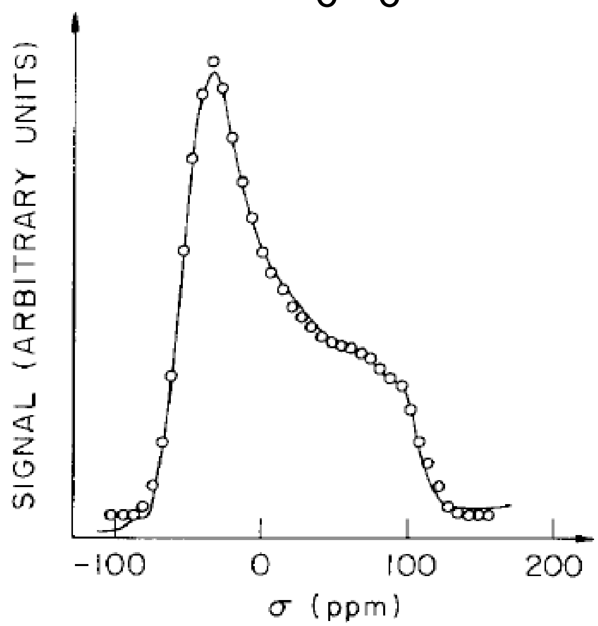
Rotational averaging of chemical shift powder patterns.

^{19}F Shielding Tensors from Coherently Narrowed NMR Powder Spectra*

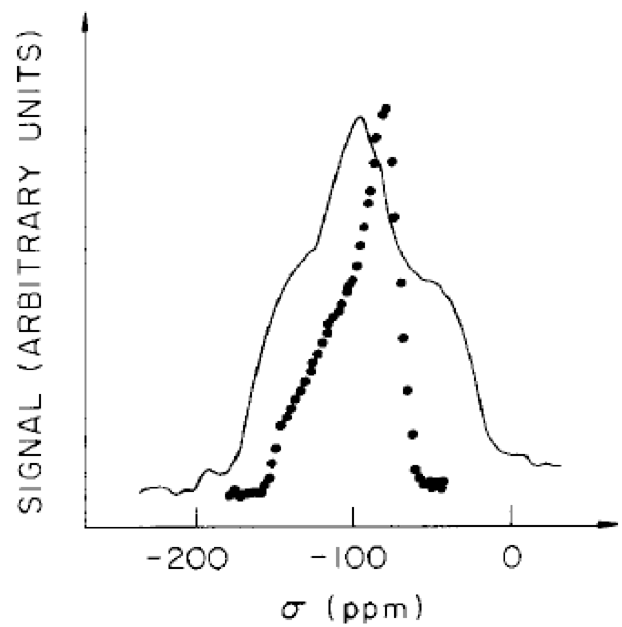
M. MEHRING, R. G. GRIFFIN,† AND J. S. WAUGH

Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

C_6F_6



CF_3-



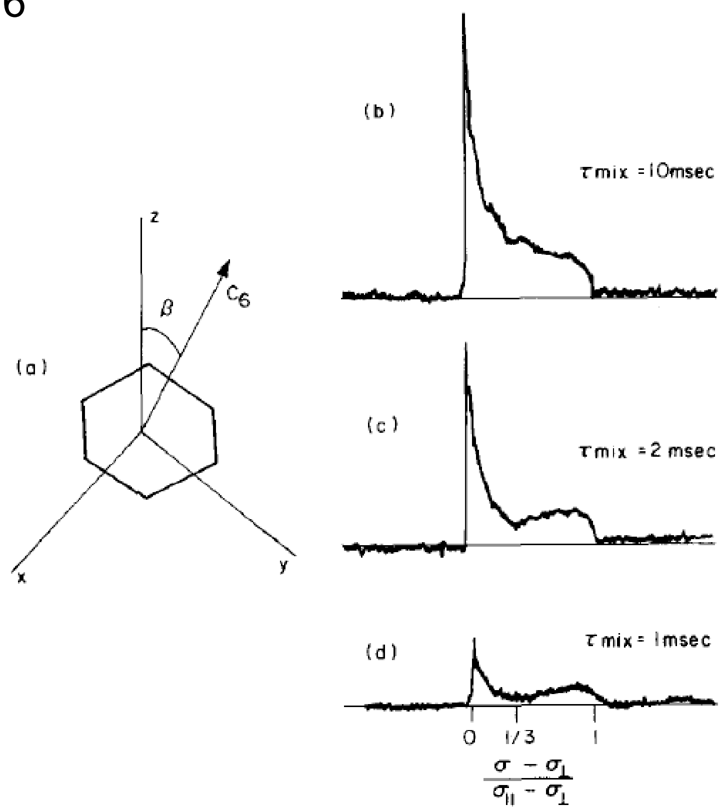
1971

Rotational averaging of 13C chemical shift powder patterns.

Proton-enhanced NMR of dilute spins in solids*

A. Pines†, M. G. Gibby‡, and J. S. Waugh
Department of Chemistry and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

C_6H_6



1973

Static vs. “hop” vs. rotational diffusion.

Dynamics of Phenylalanine in the Solid State by NMR

M. H. Frey,[†] J. A. DiVerdi,[‡] and S. J. Opella*

Contribution from the Department of Chemistry, University of Pennsylvania, Philadelphia, Pennsylvania 19104. *Received April 19, 1985*

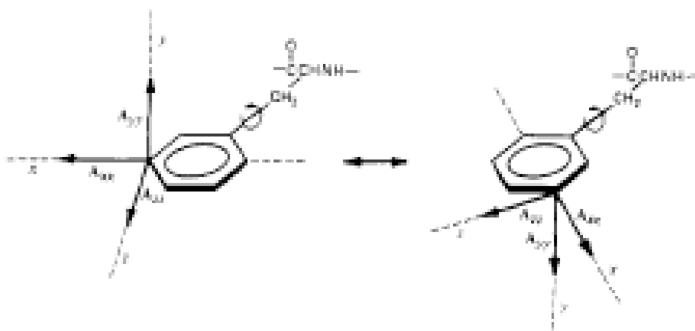


Figure 1. Effect of 180° ring flips about the C_β–C_γ bond axis on the orientation of the general spin interaction tensor in the phenyl ring.

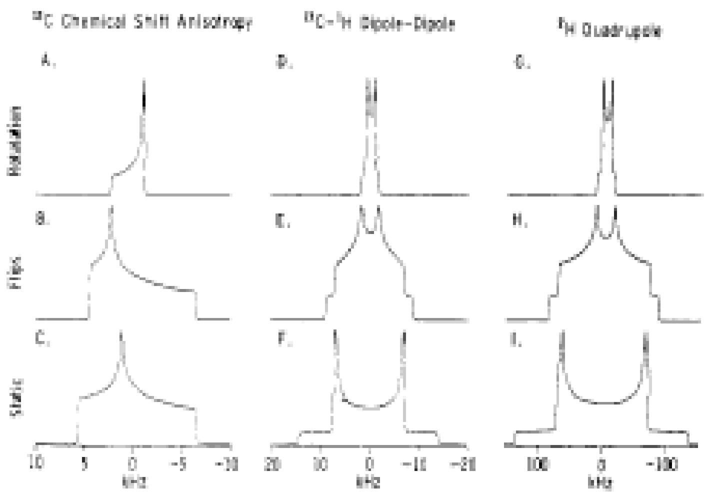
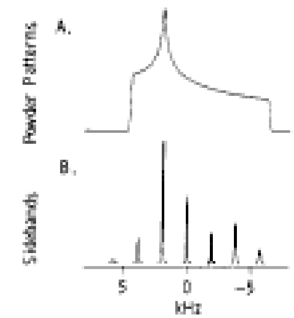


Figure 2. Calculated powder patterns for the three spin interactions described by the tensor shown in Figure 1.



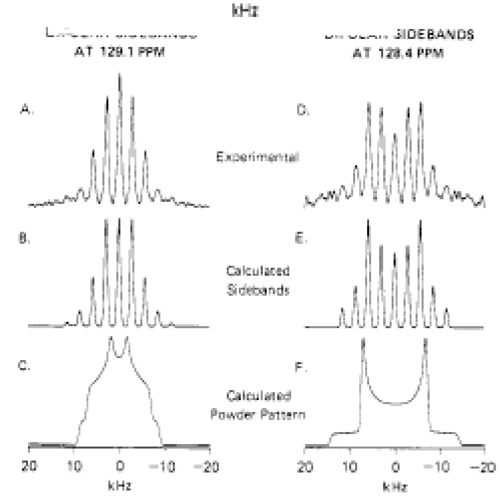


Figure 8. Selected columns from the two-dimensional data sets in Figure 7. A corresponds to 129.1 ppm and D corresponds to 128.4 ppm. B and E are the sideband intensities calculated based on the parameters of the flip averaged powder pattern C and the static powder pattern F, respectively, taking into account the experimental spinning rate and scaling factor.

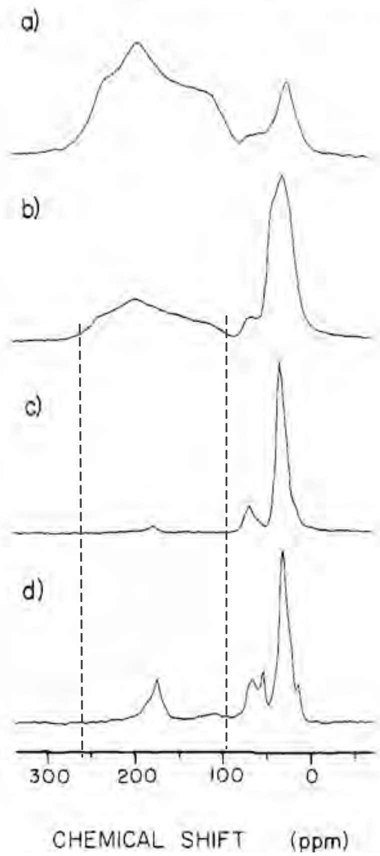
1985

Global rotational diffusion of a protein about the bilayer normal.

NMR Structural Analysis of a Membrane Protein: Bacteriorhodopsin Peptide Backbone Orientation and Motion†

B. A. Lewis,[‡,§] G. S. Harbison,[∥] J. Herzfeld,[∥] and R. G. Griffin*[,‡]
Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, and Department of Physiology and Biophysics, Harvard Medical School, Boston, Massachusetts 02115

Received January 7, 1985



3 ^{o}C in DMPC

30 ^{o}C in DMPC

"...line shape can be interpreted in terms of the orientation of the groups with respect to the diffusion axis...<u>similar to that obtained from oriented samples</u>..."

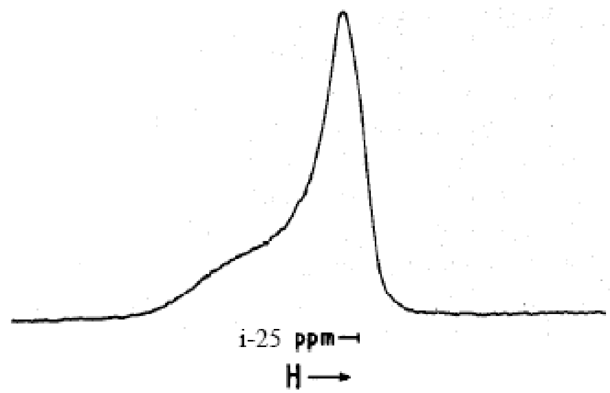
1985

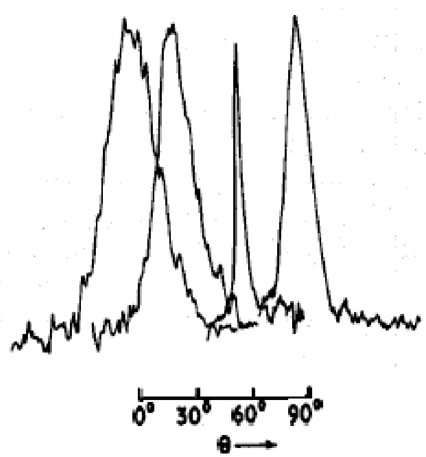
Tilted aligned samples and rotational diffusion.

Phospholipids undergo rotational diffusion about the bilayer normal, and can be aligned on glass plates.

APPLICATION OF ^{31}P NMR TO MODEL AND BIOLOGICAL MEMBRANE SYSTEMS

A. C. McLAUGHLIN, P. R. CULLIS, M. A. HEMMINGA, D. I. HOULT, G. K. RADDA, G. A. RITCHIE, P. J. SEELEY and R. E. RICHARDS
Biochemistry Department, Oxford University, 'Oxford, England

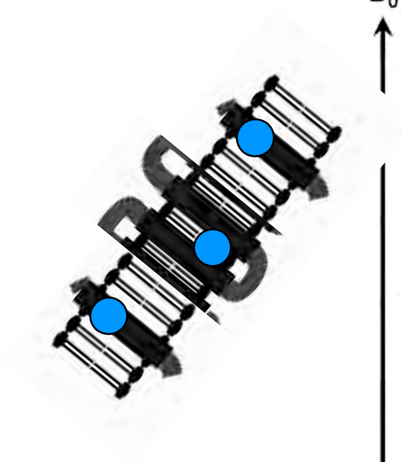


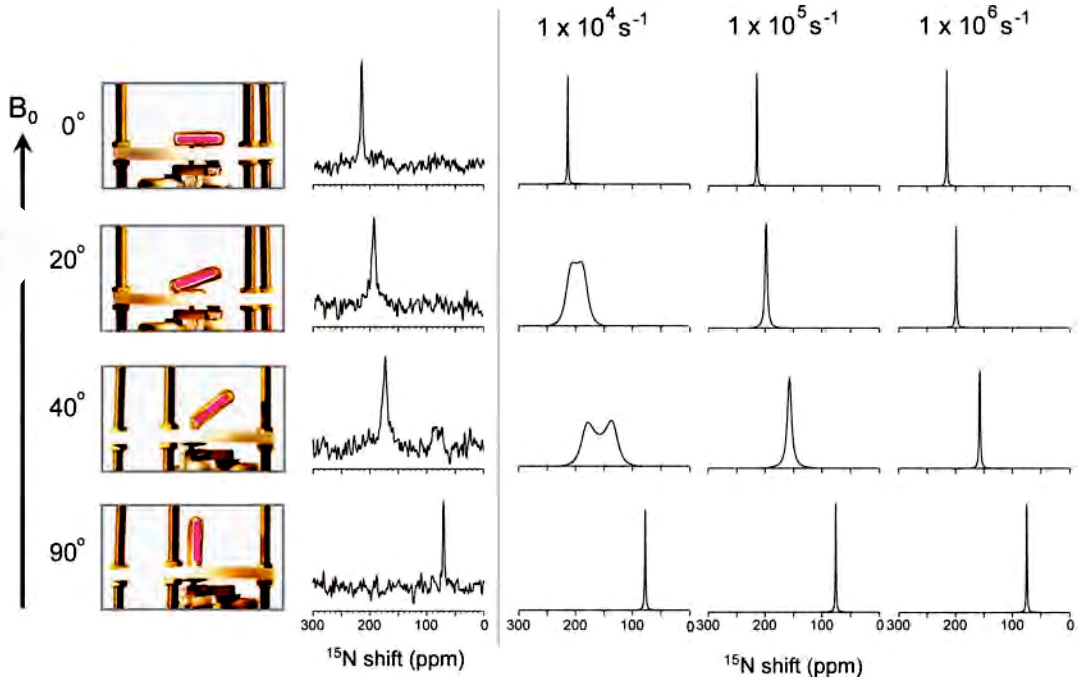


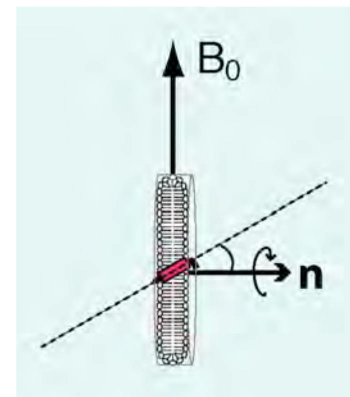
1975

Rotational diffusion of membrane proteins in aligned phospholipid bilayers by solid-state NMR spectroscopy

Sang Ho Park, Anthony A. Mrse, Alexander A. Nevzorov, Anna A. De Angelis, Stanley J. Opella *







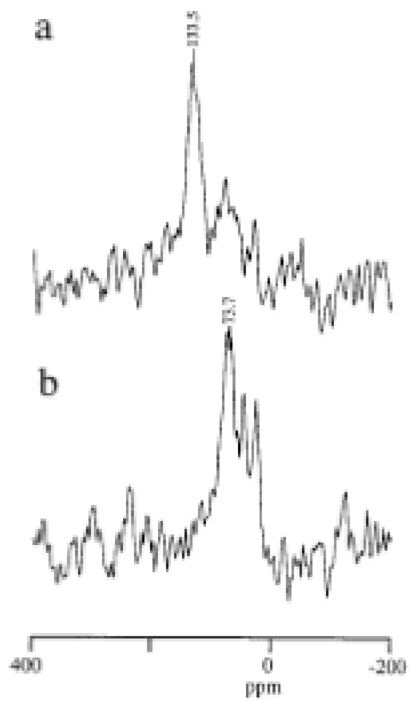
^{15}N Leu11 labeled Vpu TM in aligned bilayers on glass plates.

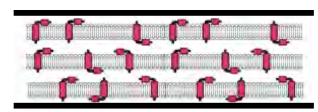
2006

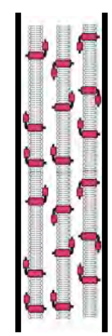
Parallel vs. perpendicular alignment of bilayers.

Transmembrane Domain of M2 Protein from Influenza A Virus Studied by Solid-State ^{15}N Polarization Inversion Spin Exchange at Magic Angle NMR

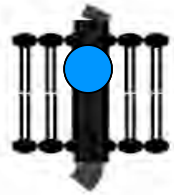
Zhiyan Song,* F. A. Kovacs,† J. Wang,† Jeffrey K. Denny,*‡ S. C. Shekar,§ J. R. Quine,*†‡ and T. A. Cross*†¶
*National High Magnetic Field Laboratory, †Institute of Molecular Biophysics, ¶Department of Chemistry, and ‡Department of Mathematics, Florida State University, Tallahassee, Florida 32306; and §Department of Biochemistry and Cellular Biology, State University of New York, Stony Brook, New York 11794 USA







2000



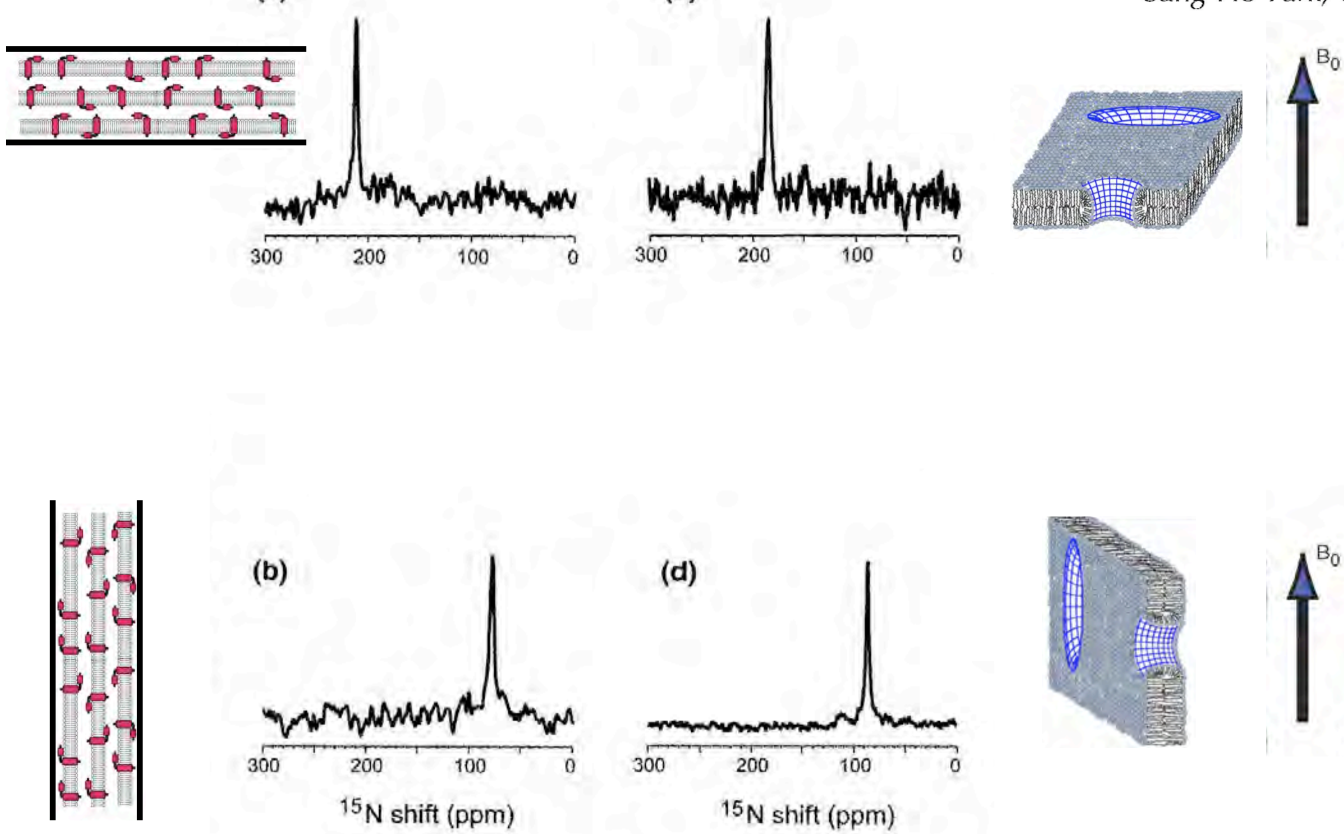
^{15}N Leu11 labeled Vpu TM in aligned bilayers.

mechanically aligned on glass plates

magnetically aligned

Uniaxial Motional Averaging of the Chemical Shift Anisotropy of Membrane Proteins in Bilayer Environments

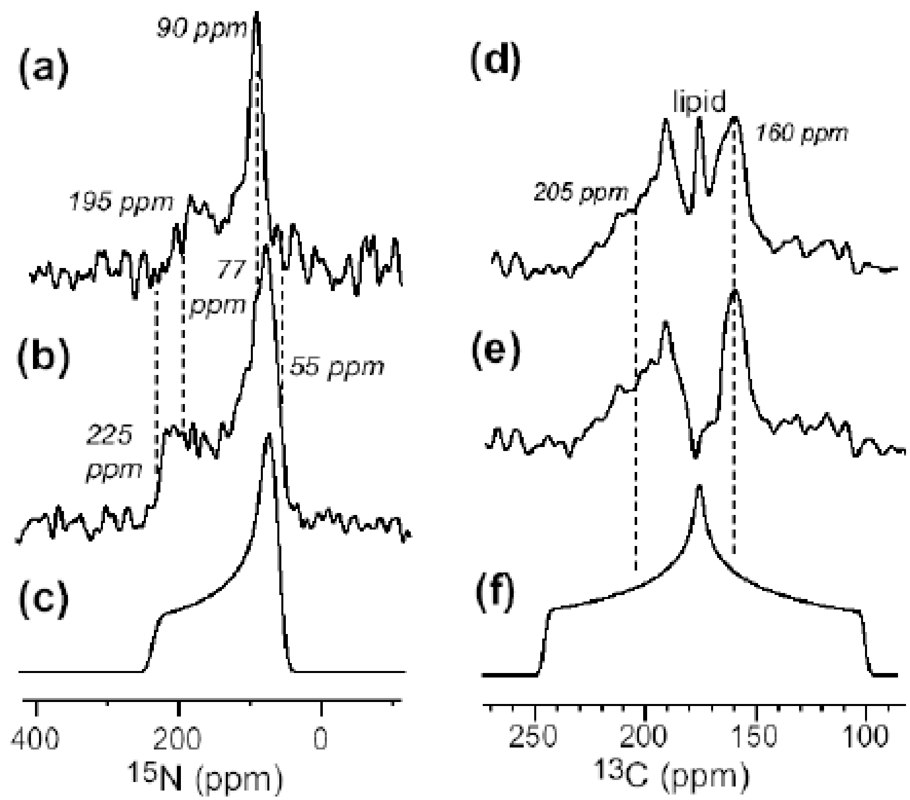
Alexander A. Nevzorov, Anna A. De Angelis, Sang Ho Park, and Stanley J. Opella



2005

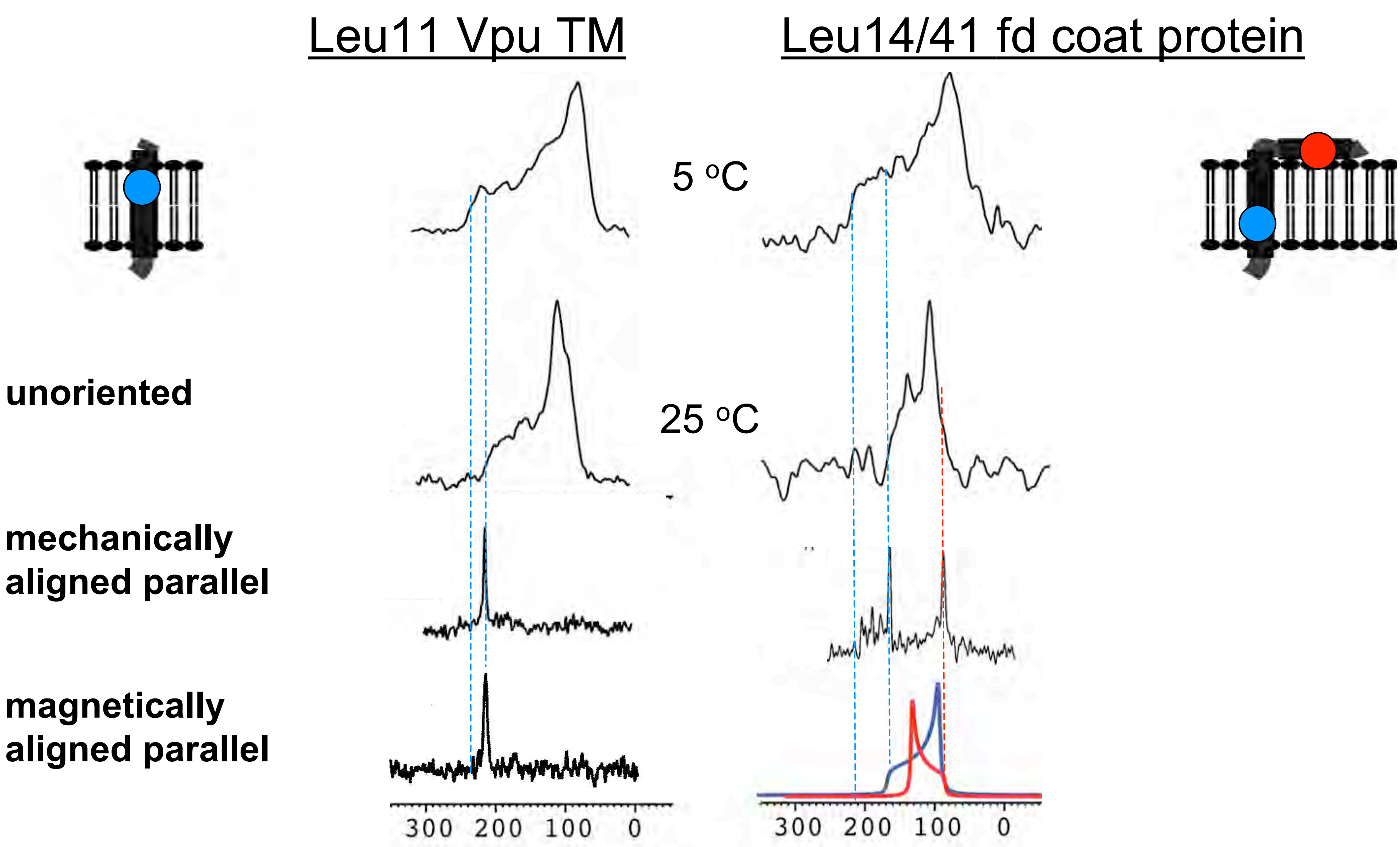
Orientation Determination of Membrane-Disruptive Proteins Using Powder Samples and Rotational Diffusion: A Simple Solid-State NMR Approach

Mei Hong* and **Tim Doherty**
Department of Chemistry, Iowa State University, Ames, IA 50011



2006

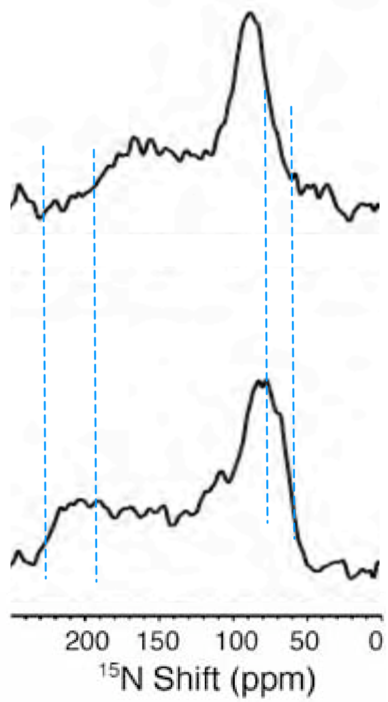
^{15}N Leu labeled membrane proteins in bilayers.



MerFt with two trans-membrane helices undergoes rapid rotational diffusion in DMPC bilayers.

40 °C

5 °C



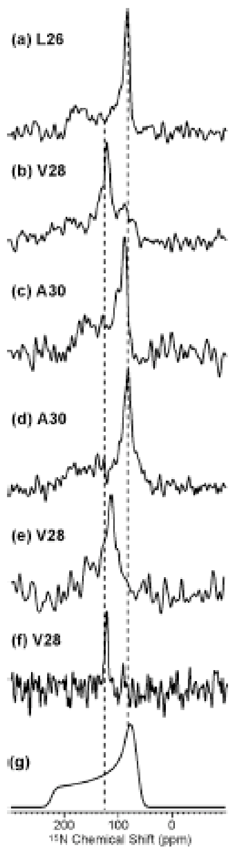
uniformly 15N labeled MerFt

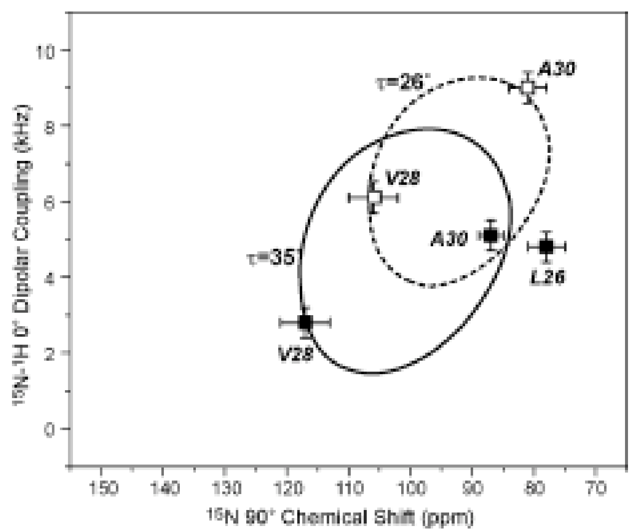
Wu Sung Son

Determining the Orientation of Uniaxially Rotating Membrane Proteins Using Unoriented Samples: A ^{2}H, ^{13}C, and ^{15}N Solid-State NMR Investigation of the Dynamics and Orientation of a Transmembrane Helical Bundle

Sarah D. Cady,† Catherine Goodman,‡ Chad D. Tatko,‡ William F. DeGrado,‡ and Mei Hong*,†

Contribution from the Department of Chemistry, Iowa State University, Ames, Iowa 50011, and Department of Biochemistry and Biophysics, University of Pennsylvania, School of Medicine, Philadelphia, Pennsylvania 19104-6059





2007

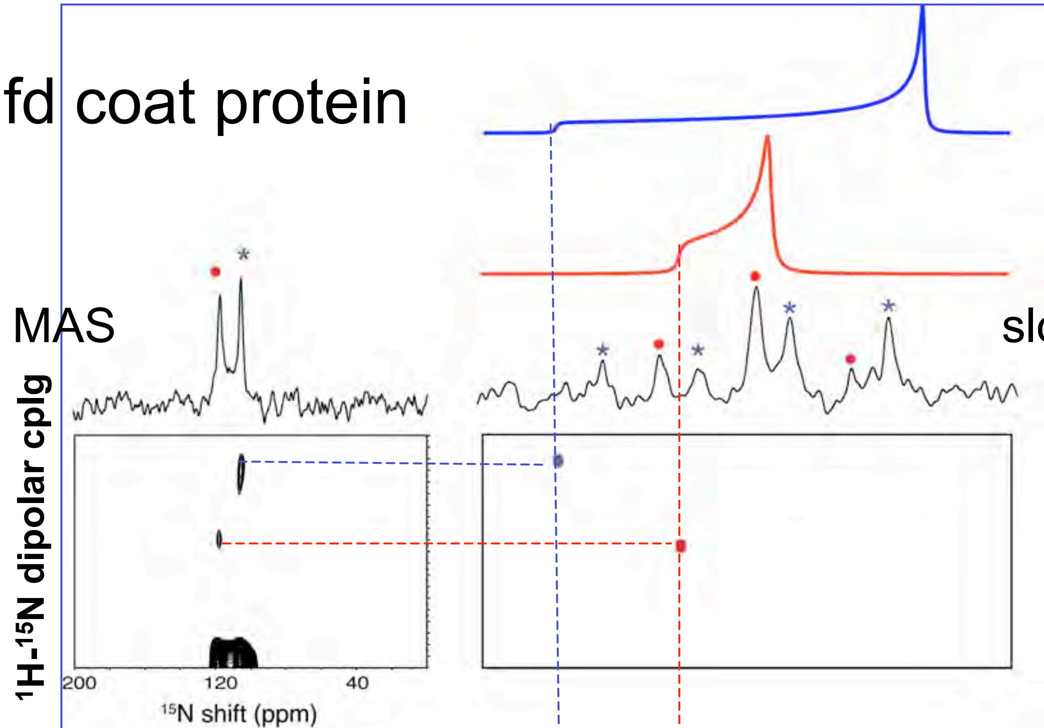
MAS of rotationally aligned samples provides the same frequencies as uniaxially aligned samples using isotropic signals.

^{15}N Trp labeled fd coat protein

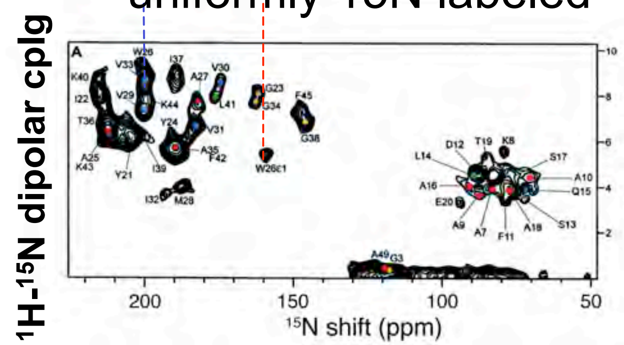
fast MAS

slow MAS

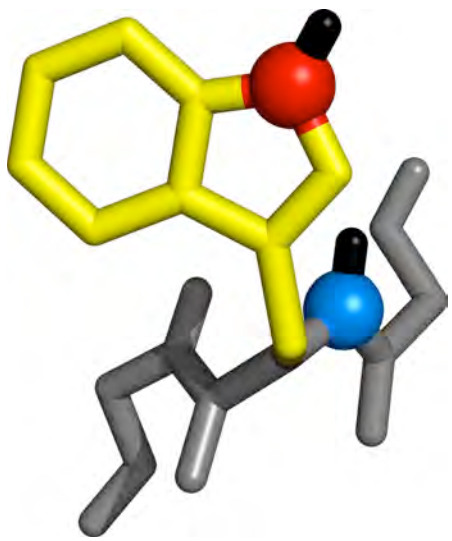
LG CP build up



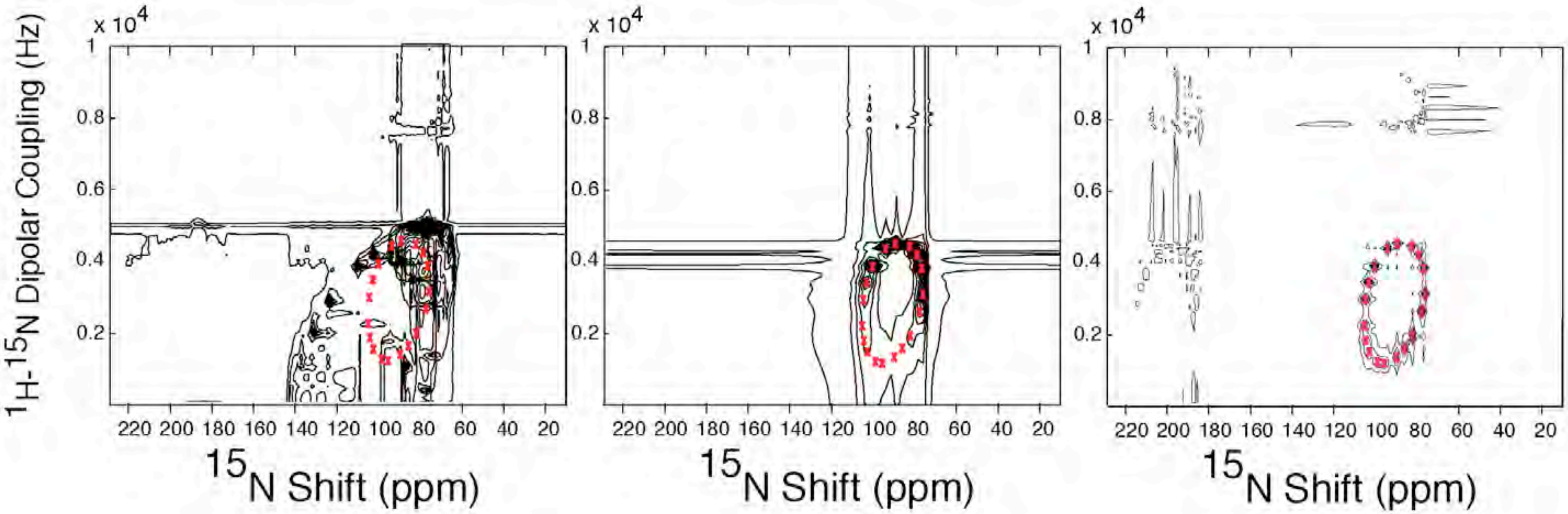
uniformly 15N labeled



mechanically aligned bilayers

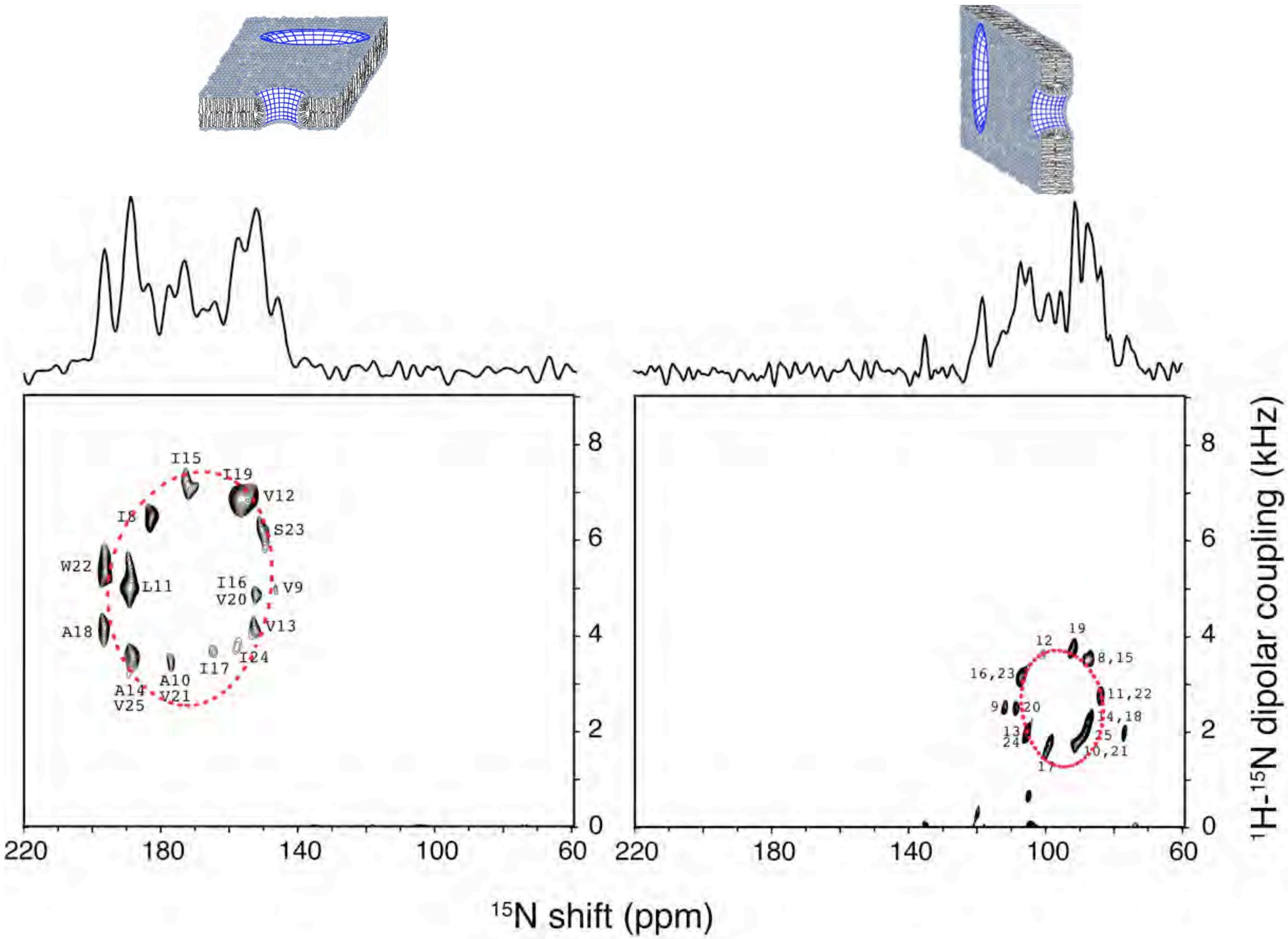


Simulated PISEMA spectra for a helix tilted 30º in perpendicular bicelles undergoing rotational diffusion about the bilayer normal.

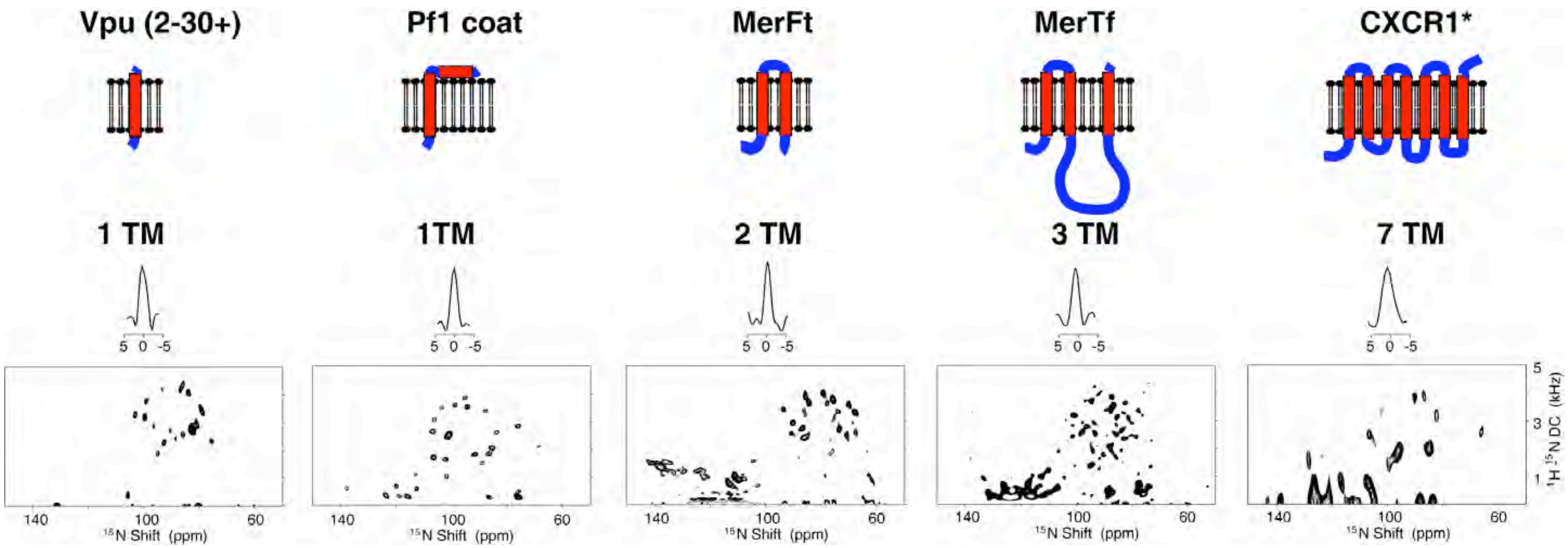


$D_{rot} = 10\ s^{-1}$ $D_{rot} = 10^4\ s^{-1}$ $D_{rot} = 10^5\ s^{-1}$

Trans-membrane domain of channel-forming viral membrane protein Vpu



Solid-state NMR spectra of membrane proteins with between 35 and 350 residues.



2GOF
2GOH
1PI7

1MZT

1NH4
1PJF
1ZN5

2H3O

* ^{15}N Ile (20 sites)

Structure Determination

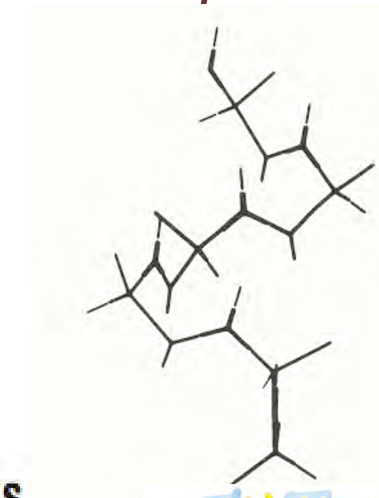
Initial structures determined by aligned sample solid-state NMR.

1985

Protein Structure by Solid State Nuclear Magnetic Resonance

Residues 40 to 45 of Bacteriophage fd Coat Protein

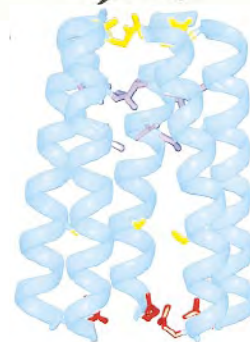
T. A. Cross† and S. J. Opella



1999

Structures of the M2 channel-lining segments from nicotinic acetylcholine and NMDA receptors by NMR spectroscopy

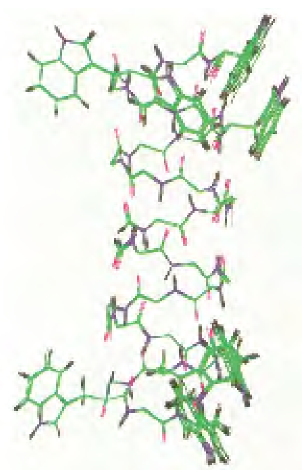
S.J. Opella[1], F.M. Marassi[1,2], J.J. Gesell[1,3], A.P. Valente[1,4], Y. Kim[1,5], M. Oblatt-Montal[6] and M. Montal[6]



2003

High-Resolution Conformation of Gramicidin A in a Lipid Bilayer by Solid-State NMR

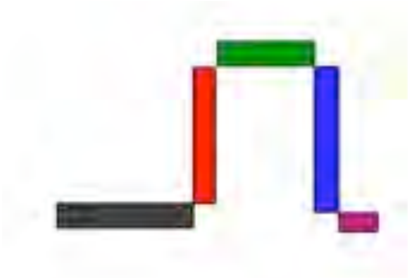
R. R. Ketchem, W. Hu, T. A. Cross*

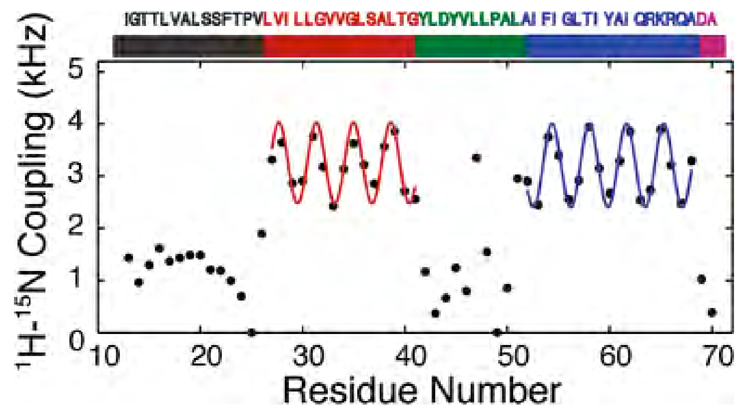


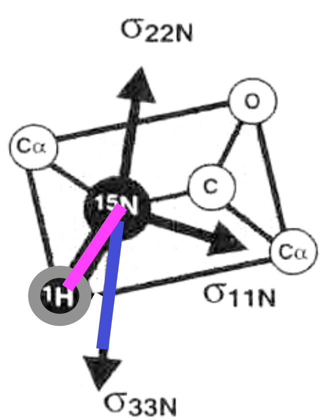
Structure Determination of a Membrane Protein with Two Trans-membrane Helices in Aligned Phospholipid Bicelles by Solid-State NMR Spectroscopy

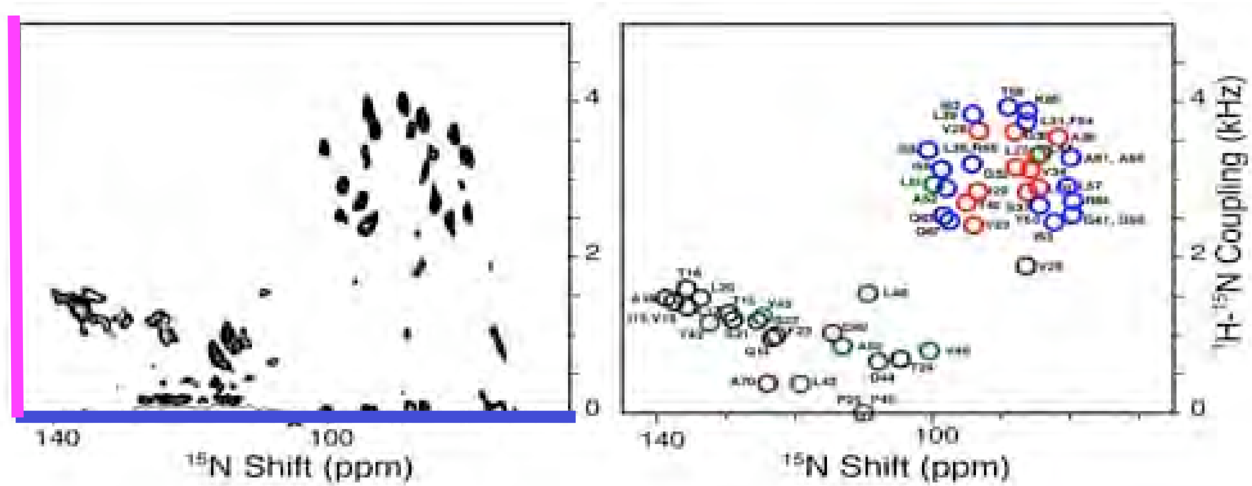
Anna A. De Angelis, Stanley C. Howell, Alexander A. Nevzorov, and Stanley J. Opella*

MerFt (60 aa)



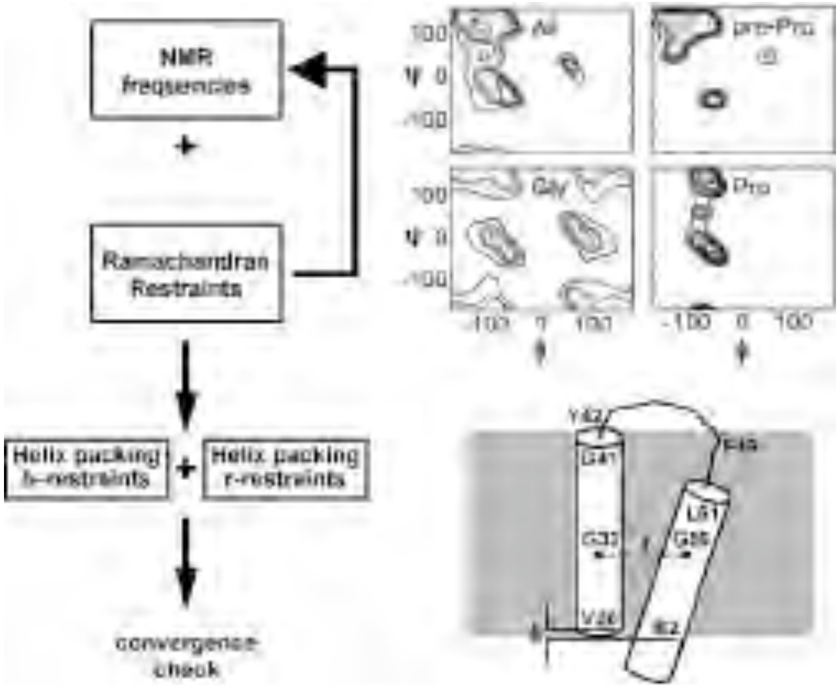






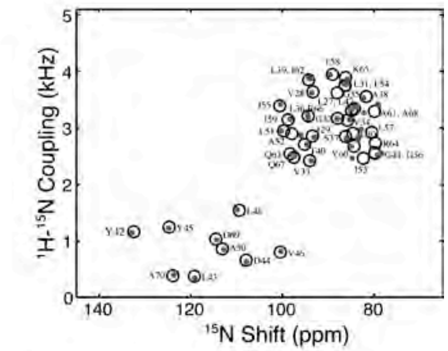
2006

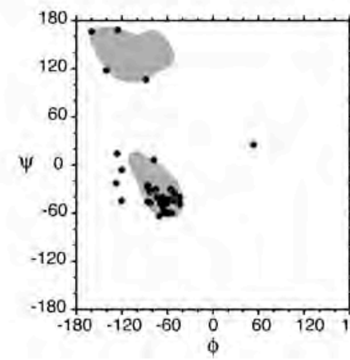
Two orientationally dependent frequencies for each residue enable calculation of three-dimensional protein structures.



2H3O

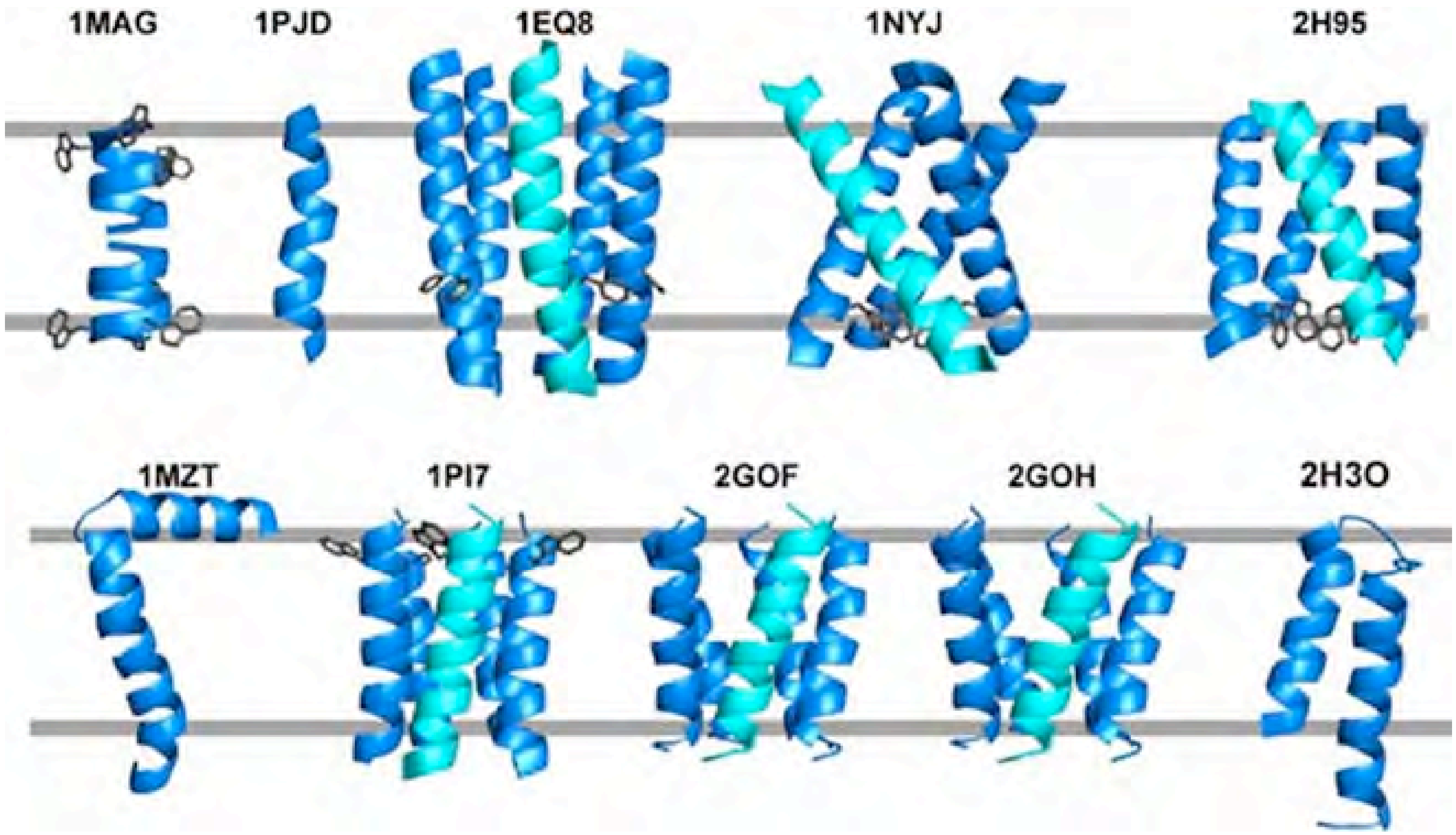
back-calculated spectrum





2006

Membrane proteins structures determined in phospholipid bilayers by solid-state NMR spectroscopy.



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