Solid-State NMR of Metal Sites in Biological Systems

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OUTLINE

INTRODUCTION

Metals in biology and chemistry: abundance, nuclear properties

QUADRUPOLAR INTERACTION

Quadrupolar Hamiltonian
First and second order quadrupolar interaction: lineshapes
Magnitude of quadrupolar interaction for different geometries
High resolution spectroscopy of quadrupolar nuclei: contrast with spin-1/2 systems

DETECTING SSNMR SPECTRA OF HALF-INTEGER QUADRUPOLAR NUCLEI

Small and moderate quadrupole couplings
Large quadrupole couplings
Sensitivity enhancement techniques
Resolution enhancement techniques
Additional practical considerations

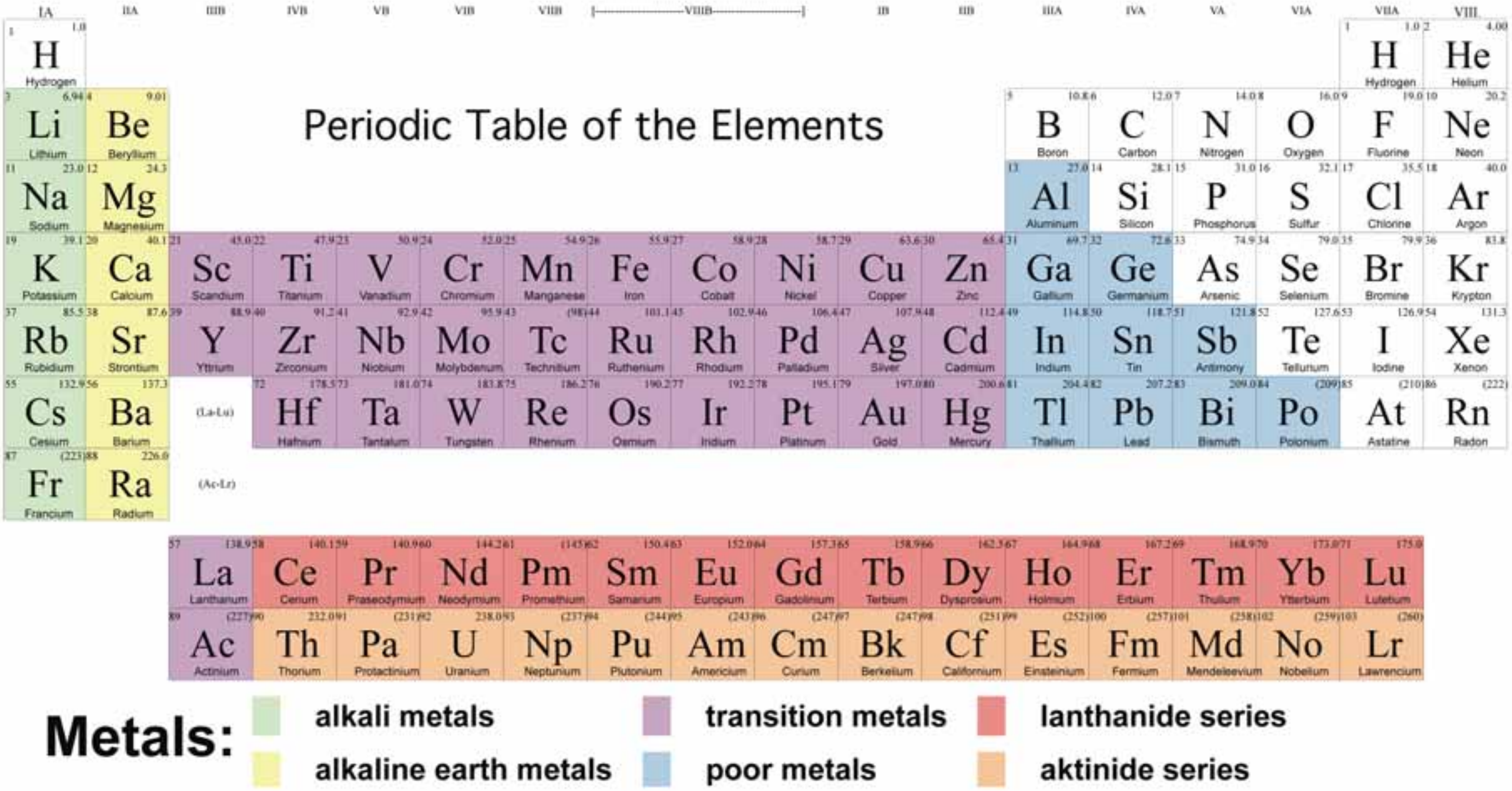
RELATING THE NMR PARAMETERS TO MOLECULAR STRUCTURE

Classical electrostatic theory
Quantum mechanical calculations of NMR parameters (EFG and CSA tensors)

EXAMPLES: SSNMR OF METALS IN BIOLOGICAL SYSTEMS

ADDITIONAL LECTURE: TUTORIAL ON QUANTUM MECHANICAL CALCULATIONS OF NMR PARAMETERS

INTRODUCTION



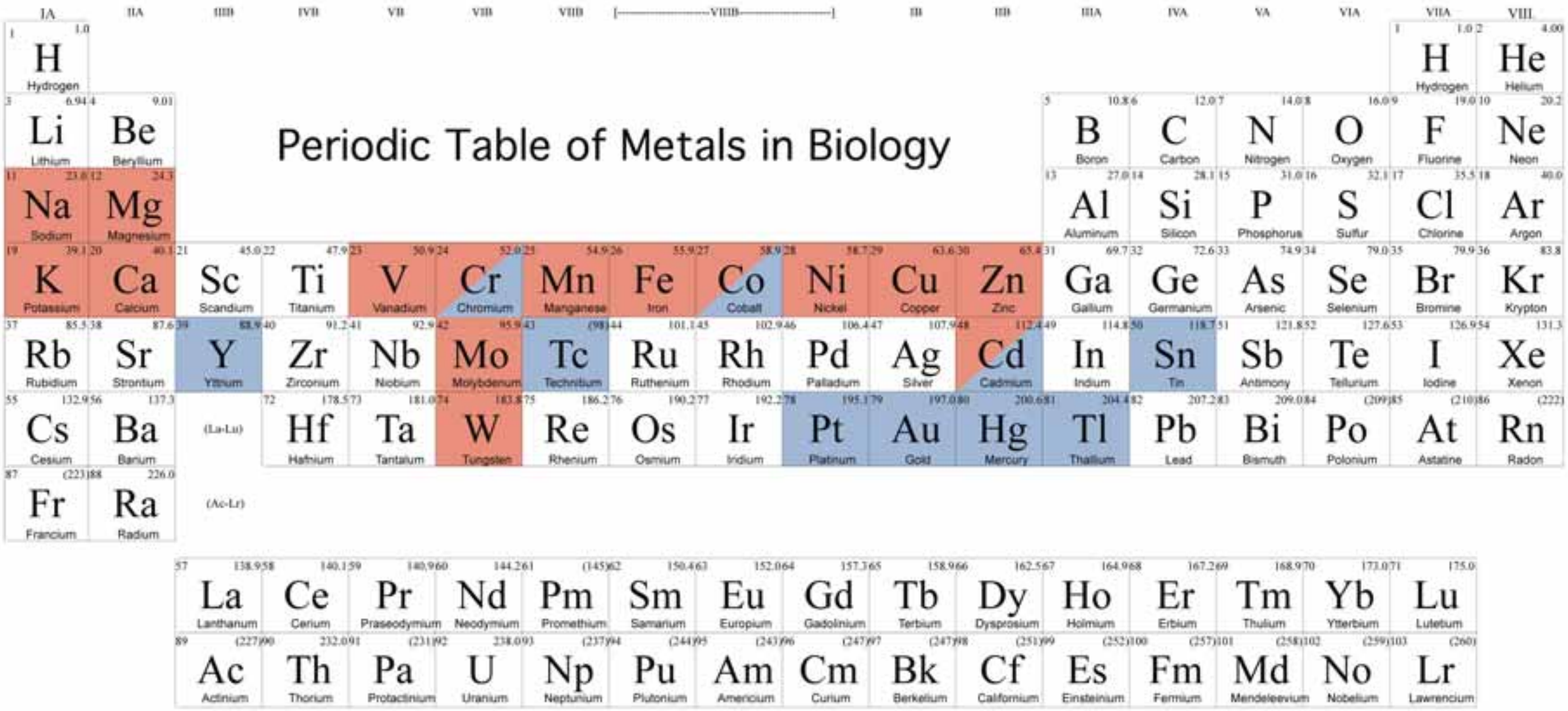
Periodic Table of the Elements

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIII
1 1.0 H Hydrogen																1 1.0 H Hydrogen	2 4.00 He Helium
3 6.94 Li Lithium	4 9.01 Be Beryllium											5 10.8 B Boron	6 12.0 C Carbon	7 14.0 N Nitrogen	8 16.0 O Oxygen	9 19.0 F Fluorine	10 20.2 Ne Neon
11 23.0 Na Sodium	12 24.3 Mg Magnesium											13 27.0 Al Aluminum	14 28.1 Si Silicon	15 31.0 P Phosphorus	16 32.1 S Sulfur	17 35.5 Cl Chlorine	18 40.0 Ar Argon
19 39.1 K Potassium	20 40.1 Ca Calcium	21 45.0 Sc Scandium	22 47.9 Ti Titanium	23 50.9 V Vanadium	24 52.0 Cr Chromium	25 54.9 Mn Manganese	26 55.9 Fe Iron	27 58.9 Co Cobalt	28 58.7 Ni Nickel	29 63.6 Cu Copper	30 65.4 Zn Zinc	31 69.7 Ga Gallium	32 72.6 Ge Germanium	33 74.9 As Arsenic	34 79.0 Se Selenium	35 79.9 Br Bromine	36 83.8 Kr Krypton
37 85.5 Rb Rubidium	38 87.6 Sr Strontium	39 88.9 Y Yttrium	40 91.2 Zr Zirconium	41 92.9 Nb Niobium	42 95.9 Mo Molybdenum	43 (98) Tc Technitium	44 101.1 Ru Ruthenium	45 102.9 Rh Rhodium	46 106.4 Pd Palladium	47 107.9 Ag Silver	48 112.4 Cd Cadmium	49 114.8 In Indium	50 118.7 Sn Tin	51 121.8 Sb Antimony	52 127.6 Te Tellurium	53 126.9 I Iodine	54 131.3 Xe Xenon
55 132.9 Cs Cesium	56 137.3 Ba Barium	(La-Lu)	72 178.5 Hf Hafnium	73 181.0 Ta Tantalum	74 183.8 W Tungsten	75 186.2 Re Rhenium	76 190.2 Os Osmium	77 192.2 Ir Iridium	78 195.1 Pt Platinum	79 197.0 Au Gold	80 200.6 Hg Mercury	81 204.4 Tl Thallium	82 207.2 Pb Lead	83 209.0 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon
87 (223) Fr Francium	88 226.0 Ra Radium	(Ac-Lr)															
		57 138.9 La Lanthanum	58 140.1 Ce Cerium	59 140.9 Pr Praseodymium	60 144.2 Nd Neodymium	61 (145) Pm Promethium	62 150.4 Sm Samarium	63 152.0 Eu Europium	64 157.3 Gd Gadolinium	65 158.9 Tb Terbium	66 162.5 Dy Dysprosium	67 164.9 Ho Holmium	68 167.2 Er Erbium	69 168.9 Tm Thulium	70 173.0 Yb Ytterbium	71 175.0 Lu Lutetium	
		89 (227) Ac Actinium	90 232.0 Th Thorium	91 (231) Pa Protactinium	92 238.0 U Uranium	93 (237) Np Neptunium	94 (244) Pu Plutonium	95 (243) Am Americium	96 (247) Cm Curium	97 (247) Bk Berkelium	98 (251) Cf Californium	99 (252) Es Einsteinium	100 (257) Fm Fermium	101 (258) Md Mendeleevium	102 (259) No Nobelium	103 (260) Lr Lawrencium	

Metals:

🟩 **alkali metals**
🟨 **alkaline earth metals**
🟪 **transition metals**
🟦 **poor metals**
🟥 **lanthanide series**
🟧 **aktinide series**

PERIODIC TABLE OF METALS IN BIOLOGY



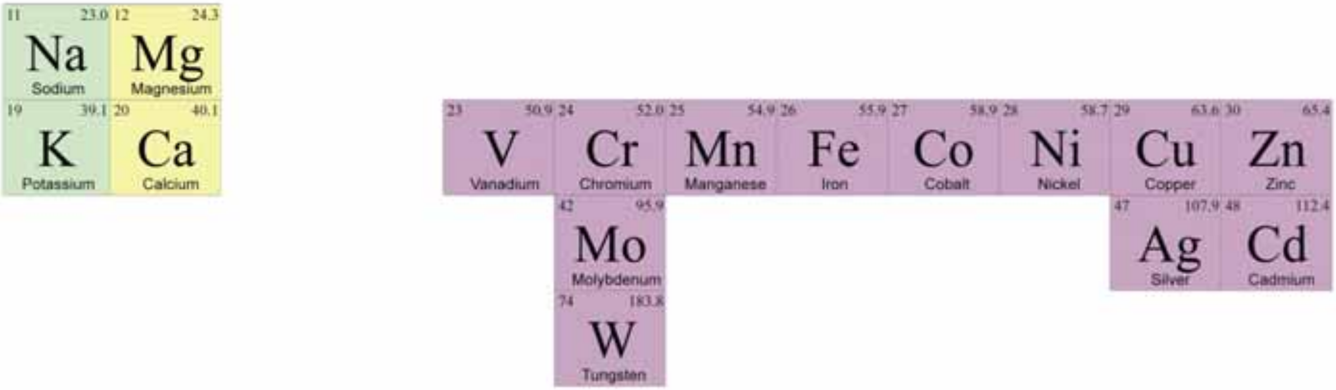
Periodic Table of Metals in Biology

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIII
H Hydrogen																H Hydrogen	He Helium
Li Lithium	Be Beryllium											B Boron	C Carbon	N Nitrogen	O Oxygen	F Fluorine	Ne Neon
🟥 Na Sodium	🟥 Mg Magnesium											Al Aluminum	Si Silicon	P Phosphorus	S Sulfur	Cl Chlorine	Ar Argon
🟥 K Potassium	🟥 Ca Calcium	Sc Scandium	Ti Titanium	🟥 V Vanadium	🟥🟦 Cr Chromium	🟥 Mn Manganese	🟥 Fe Iron	🟥🟦 Co Cobalt	🟥 Ni Nickel	🟥 Cu Copper	🟥 Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium	Br Bromine	Kr Krypton
Rb Rubidium	Sr Strontium	🟦 Y Yttrium	Zr Zirconium	Nb Niobium	🟥 Mo Molybdenum	🟦 Tc Technitium	Ru Ruthenium	Rh Rhodium	Pd Palladium	Ag Silver	🟥🟦 Cd Cadmium	In Indium	🟦 Sn Tin	Sb Antimony	Te Tellurium	I Iodine	Xe Xenon
Cs Cesium	Ba Barium	(La-Lu)	Hf Hafnium	Ta Tantalum	🟥 W Tungsten	Re Rhenium	Os Osmium	Ir Iridium	🟦 Pt Platinum	🟦 Au Gold	🟦 Hg Mercury	🟦 Tl Thallium	Pb Lead	Bi Bismuth	Po Polonium	At Astatine	Rn Radon
Fr Francium	Ra Radium	(Ac-Lr)															
		La Lanthanum	Ce Cerium	Pr Praseodymium	Nd Neodymium	Pm Promethium	Sm Samarium	Eu Europium	Gd Gadolinium	Tb Terbium	Dy Dysprosium	Ho Holmium	Er Erbium	Tm Thulium	Yb Ytterbium	Lu Lutetium	
		Ac Actinium	Th Thorium	Pa Protactinium	U Uranium	Np Neptunium	Pu Plutonium	Am Americium	Cm Curium	Bk Berkelium	Cf Californium	Es Einsteinium	Fm Fermium	Md Mendeleevium	No Nobelium	Lr Lawrencium	

🟥 **naturally occurring metals** 🟦 **metals used as probes or drugs**

ABOUT 1/3 OF ALL PROTEINS CONTAIN METALS

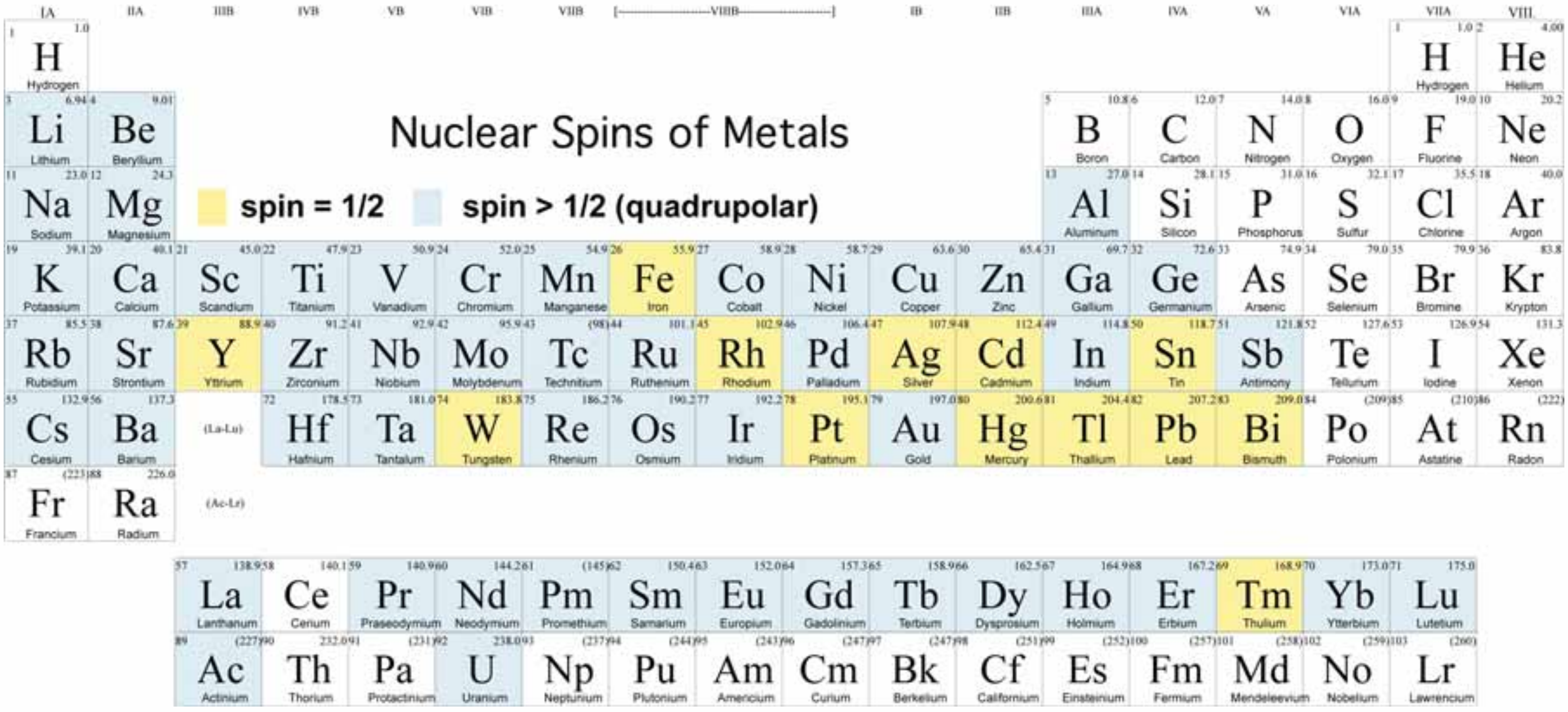
BIOLOGICAL FUNCTIONS OF METALS



Na	Sodium	charge carrier; osmotic balance
K	Potassium	charge carrier, osmotic balance
Mg	Magnesium	structure; hydrolase; isomerase
Ca	Calcium	structure; trigger; charge carrier
V	Vanadium	nitrogen fixation; oxidase
Cr	Chromium	essential trace element; possible involvement in glucose tolerance
Mo	Molybdenum	nitrogen fixation; oxidase; oxo transfer
W	Tungsten	dehydrogenase
Mn	Manganese	photosynthesis; oxidase; structure
Fe	Iron	oxidase; dioxygen transport and storage; electron transfer; nitrogen fixation
Co	Cobalt	oxidase; alkyl group transfer
Ni	Nickel	hydrogenase; hydrolase
Cu	Copper	oxidase; dioxygen transport; electron transfer
Zn	Zinc	structure; hydrolase

Adapted from S. Lippard and J. Berg “Principles of Bioinorganic Chemistry”

MAGNETIC PROPERTIES OF METALS



Nuclear Spins of Metals

🟨 **spin = 1/2** 🟦 **spin > 1/2 (quadrupolar)**

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIII
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11 23.0 🟦 Na Sodium	12 24.3 🟦 Mg Magnesium											13 27.0 🟦 Al Aluminum	14 28.1 Si Silicon	15 31.0 P Phosphorus	16 32.1 S Sulfur	17 35.5 Cl Chlorine	18 40.0 Ar Argon
19 39.1 🟦 K Potassium	20 40.1 🟦 Ca Calcium	21 45.0 🟦 Sc Scandium	22 47.9 🟦 Ti Titanium	23 50.9 🟦 V Vanadium	24 52.0 🟦 Cr Chromium	25 54.9 🟦 Mn Manganese	26 55.9 🟨 Fe Iron	27 58.9 🟦 Co Cobalt	28 58.7 🟦 Ni Nickel	29 63.6 🟦 Cu Copper	30 65.4 🟦 Zn Zinc	31 69.7 🟦 Ga Gallium	32 72.6 🟦 Ge Germanium	33 74.9 As Arsenic	34 79.0 Se Selenium	35 79.9 Br Bromine	36 83.8 Kr Krypton
37 85.5 🟦 Rb Rubidium	38 87.6 🟦 Sr Strontium	39 88.9 🟨 Y Yttrium	40 91.2 🟦 Zr Zirconium	41 92.9 🟦 Nb Niobium	42 95.9 🟦 Mo Molybdenum	43 (98) 🟦 Tc Technitium	44 101.1 🟦 Ru Ruthenium	45 102.9 🟨 Rh Rhodium	46 106.4 🟦 Pd Palladium	47 107.9 🟨 Ag Silver	48 112.4 🟨 Cd Cadmium	49 114.8 🟦 In Indium	50 118.7 🟨 Sn Tin	51 121.8 🟦 Sb Antimony	52 127.6 Te Tellurium	53 126.9 I Iodine	54 131.3 Xe Xenon
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SPIN-1/2 METALS IN BIOLOGY

NATURALLY OCCURING SPIN-1/2 METALS

^{57}Fe- detection of low-spin ferrous Fe^{2+} in ferrocenes and porphyrins, myoglobins, and cytochrome c (Baltzer et al.: J. Am. Chem. Soc. 1984, Chem. Comm. 1985, J. Am. Chem. Soc. 1987, Chem. Comm. 1987)

SPIN-1/2 METALS USED AS NMR PROBES OR DRUGS

^{111}Cd- replacement of native Zn(II), Ca(II), Mg(II), Mn(II), Fe(II), Cu(II) sites in proteins (e.g., calmodulin, transferrin, alkaline phosphatase, azurin, plastocyanin, glucocorticoid receptor, etc.)

^{119}Sn- structural probe of protoporphyrin-hemoprotein interactions, in organotin antibiotics and antitumor drugs

^{195}Pt- structural probe in Pt complexes used as antitumor agents to probe interactions with DNA

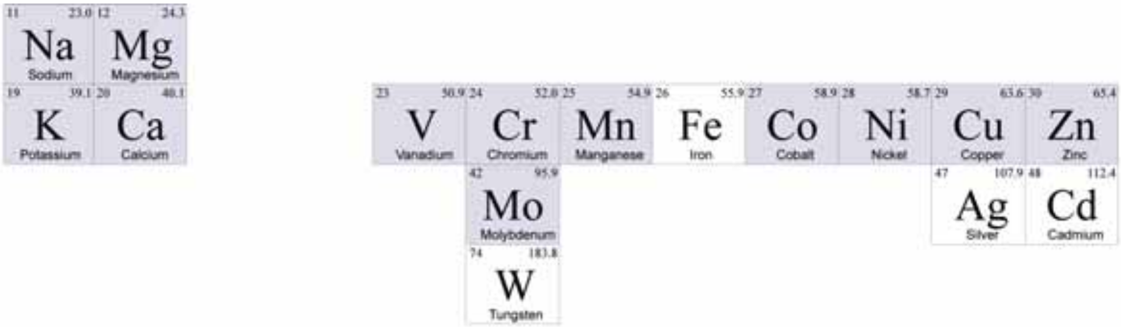
^{199}Hg- replacement of native Zn(II), Cu(II), Fe(II) sites in proteins (e.g., carbonic anhydrase, azurin, plastocyanin, rusticyanin, rubredoxin, Gal4, MerR, and MerP)

^{205}Tl^{+}- structural probe for monovalent cation binding sites (K^{+}, Na^{+}) in ATPases, protein C, S-adenosylmethioneine synthetase, and pyruvate kinase;

^{205}Tl^{3+}- probe of Fe^{3+} sites in transferrins

Reviewed in G. Oz, D. L. Pountney, and I. M. Armitage, Biochem. Cell. Biol. 76: 223-224 (1998)

QUADRUPOLAR METALS IN BIOLOGY



	Examples of metalloproteins
Na	Na^+ ion channels, Na^+-K^+-ATPase,
K	K^+ ion channels, Na^+-K^+-ATPase,
Mg	restriction endonucleases, Mg^{2+}/Ca^{2+}-ATPase, phosphatase, phosphoglucomutase, DNA polymerase
Ca	thermolysin, phospholipase A_2, Mg^{2+}/Ca^{2+}-ATPase, neutral protease
V	nitrogenase, haloperoxidases
Cr	essential trace element but specific proteins are unknown
Mo	nitrogenase, xanthine oxidase, nitrate reductase, formate dehydrogenase, dimethylsulfoxide reductase, sulfite oxidase
Mn	SOD, photosystem II, arginase, catalase, xylose isomerase, ribonuclease H, phosphotriesterase, enolase
Co	Coenzyme-B12 dependent enzymes: glutamate mutase, diol dehydrase, ribonucleotide reductase, ethanolamine ammonia lyase, methionine aminopeptidase, glucose isomerase, Co transporters
Ni	Ni-Fe hydrogenases; hydrolases
Cu	azurin, galactose oxidase, nitrogenase, plastocyanin, hemocyanin, Cu-Zn SOD
Zn	liver alcohol dehydrogenase, carbonic anhydrase, carboxypeptidease A, Cu-Zn SOD

UNDERSTANDING GEOMETRIC AND ELECTRONIC STRUCTURE OF THE METAL CENTERS- IMPORTANT FOR UNDERSTANDING THE FUNCTION OF THE METALLOPROTEINS; SSNMR- DIRECT PROBE

METALS NMR IN BIOLOGICAL SOLIDS: INFORMATION CONTENT

Presence of a particular metal site (sometimes indiscernible in X-ray structures)

Geometry of metal sites

Electronic structure of metal sites (i.e., interactions with surrounding ligands and/or solvent molecules)

Protonation states of metal cofactors/ligands

Identification of polymorphs

Dynamics of metals and/or coordinated ligands

This information- sheds light on chemical reactivity of metal sites in metallobiomolecules, often unavailable from other techniques

SSNMR SPECTROSCOPY OF QUADRUPOLAR NUCLEI IN BIOLOGICAL SYSTEMS

UNTIL RECENTLY HAS BEEN CONSIDERED IMPRACTICAL:

LOW SENSITIVITY
BROAD LINES
COMPLEX SYMMETRY OF QUADRUPOLAR INTERACTION

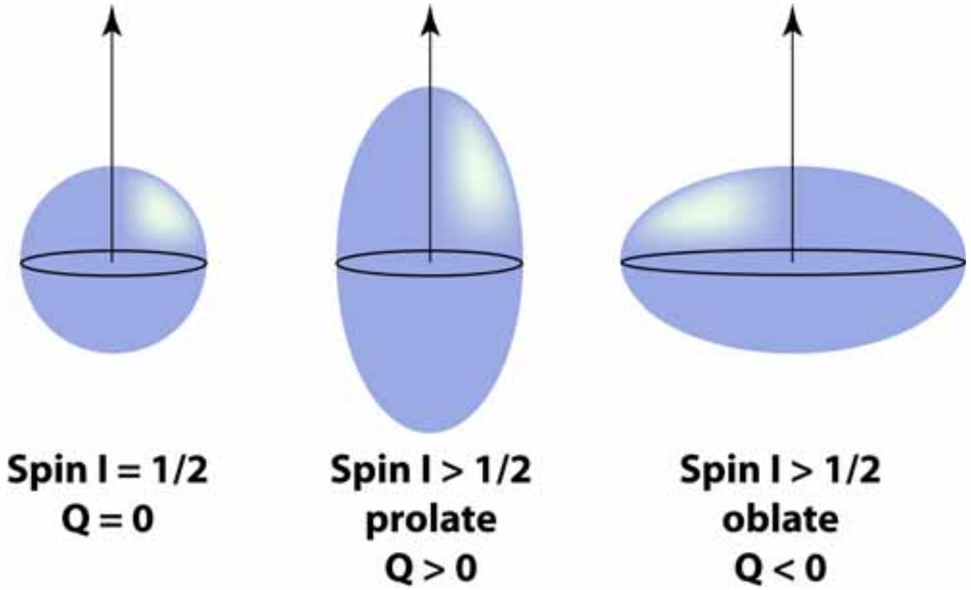
QUADRUPOLAR NUCLEI

NUCLEI WITH SPIN I > 1/2

HAVE A NON-SPHERICAL CHARGE DISTRIBUTION, POSSESS A NUCLEAR QUADRUPOLE MOMENT, eQ

THE NUCLEAR QUADRUPOLE MOMENT, eQ, INTERACTS WITH THE ELECTRIC FIELD GRADIENT, V, AT THE NUCLEUS

NUCLEAR CHARGE DISTRIBUTION



ELECTROSTATIC INTERACTION OF THE NUCLEUS WITH ITS ENVIRONMENT

$$H = \int \rho(x) V(x) d^3 x$$

$\rho(x)$ **Nuclear charge density**

$V(x)$ **Electrostatic potential (all charges other than nucleus under consideration)**

EXPAND THE POTENTIAL ABOUT THE NUCLEAR CENTER OF MASS:

$$H = \int d^3 x \rho(x) \left\{ V_O + \sum_J \left(\frac{\partial V}{\partial x_J} \right)_0 x_j + \frac{1}{2} \sum_{j,k} \left(\frac{\partial^2 V}{\partial x_J \partial x_k} \right)_0 x_j x_k + \ldots \right\}$$

$\int d^3 x \rho(x) = Ze$ **- nuclear charge**

$\int d^3 x \rho(x) x_j \equiv P_j$ **- electric dipole moment**

$\int d^3 x \rho(x) x_j x_k \equiv Q_{jk}'$ **- electric quadrupole moment tensor**

M. H. Cohen and F. Reif “Quadrupole Effects in Nuclear Magnetic Resonance Studies in Solids” Solid St. Phys. 5: 321-438 (1957)

ELECTROSTATIC INTERACTION OF THE NUCLEUS WITH ITS ENVIRONMENT

EXPAND THE POTENTIAL ABOUT THE NUCLEAR CENTER OF MASS:

$$H = ZeV_O + \sum_J P_j \left(\frac{\partial V}{\partial x_J}\right)_0 x_j + \frac{1}{2}\sum_{j,k} Q_{jk}{}' \left(\frac{\partial^2 V}{\partial x_J \partial x_k}\right)_0 x_j x_k + \ldots$$

electrostatic energy of a point nucleus

electric dipole term (vanishes)

quadrupolar interaction

$$V_{jk} \equiv \frac{\partial^2 V}{\partial x_j \partial x_k} = -\frac{\partial E_k}{\partial x_j} \quad - electric\ \ field\ gradient\ tensor\ elements$$

$$where\ \ E_k = -\frac{\partial V}{\partial x_k} - electric\ \ field$$

M. H. Cohen and F. Reif "Quadrupole Effects in Nuclear Magnetic Resonance Studies in Solids" Solid St. Phys. 5: 321-438 (1957)

NUCLEAR ELECTRIC QUADRUPOLE MOMENT

MEASURES THE DEPARTURE OF THE NUCLEAR CHARGE DISTRIBUTION FROM SPHERICAL SYMMETRY

$$eQ \equiv \int \rho_{II}(x)\left(3z^2 - r^2\right)d^3x$$

$\rho_{II}(x)$ - **expectation value of the nuclear charge density (state with I = m)**

For spherically symmetric $\rho(\mathbf{x})$, Q = 0

PROPERTIES OF Q:

Has dimensions of an area, of the order of magnitude r_n^2;
r_n- nuclear radius, 10^{-13} - 10^{-12} cm;
$Q \sim r_n^2 \sim 10^{-24}$ cm^2

M. H. Cohen and F. Reif "Quadrupole Effects in Nuclear Magnetic Resonance Studies in Solids" Solid St. Phys. 5: 321-438 (1957)

NUCLEAR ELECTRIC QUADRUPOLE MOMENT: UNITS AND SIGN CONVENTIONS

THE QUADRUPOLE COUPLING CONSTANT FOR NUCLEUS X IS GIVEN AS

$$C_Q^X = \frac{e^2 q Q^X}{a_0^3 h} = \frac{e V_{ZZ}^{PAS} Q^X}{a_0^3 h}$$

where Q^x is the quadrupole moment for nucleus X.

The constants are given as

Electron's charge: $e = 4.803242 \times 10^{-10}$ esu = 4.803242×10^{-10} $g^{1/2}\,cm^{3/2}s^{-1}$

Planck constant: $h = 6.626176 \times 10^{-27}$ ergs = 6.626176×10^{-27} gcm^2s^{-1}

First Bohr orbit radius in H: $a_o = 0.52917706 \times 10^{-8}$ cm

using these values ...

$$[e^2/(a_o^3 h)] \times 10^{-24}\ cm^2 = 2.349649 \times 10^8\ Hz$$

Slide material courtesy of Paul Ellis

NUCLEAR ELECTRIC QUADRUPOLE MOMENT: UNITS AND SIGN CONVENTIONS

SOME TYPICAL VALUES OF Q^X X 10^{24} ARE:

^{95}Mo:	$Q^{Mo} = 0.16\ cm^2$	($0.022\ cm^2$)
^{67}Zn:	$Q^{Zn} = 0.15\ cm^2$	($0.150\ cm^2$)
^{63}Cu:	$Q^{Cu} = 0.16\ cm^2$	($0.220\ cm^2$)
^{43}Ca:	$Q^{Ca} = 0.2 \pm 0.1\ cm^2$	($-0.0408\ cm^2$ limited accuracy)
^{37}Cl	$Q^{Cl} = (-0.0646\ cm^2)$	
^{35}Cl	$Q^{Cl} = (-0.082\ cm^2)$	
^{33}S:	$Q^{S} = -0.064\ cm^2$	($-0.0678\ cm^2$)
^{27}Al:	$Q^{Al} = 0.149\ cm^2$	($0.1403\ cm^2$)
^{25}Mg:	$Q^{Mg} = 0.22\ cm^2$	($0.1994\ cm^2$)
^{23}Na:	$Q^{Na} = 0.12\ cm^2$	($0.1074\ cm^2$)
^{17}O:	$Q^{0} = -0.026\ cm^2$	
^{14}N:	$Q^{N} = 0.016\ cm^2$	
^{9}Be:	$Q^{Be} = 0.052\ cm^2$	
^{7}Li:	$Q^{Li} = -0.045\ cm^2$	($-0.0401\ cm^2$)
^{2}H:	$Q^{H} = 0.00273\ cm^2$	($0.002860\ cm^2$)

The values in parenthesis are those deduced by P. Pyykkö [Z. Naturforsch. **47a**, 189-196 (1992)].

Slide material courtesy of Paul Ellis

NUCLEAR ELECTRIC QUADRUPOLE MOMENT: UNITS AND SIGN CONVENTIONS

THEREFORE, WE CAN WRITE (USING PYYKKÖ'S VALUES):

$C_q^{Mo} = q_{zz}5.16923\ \text{MHz}$

$C_q^{Zn} = q_{zz}35.24474\ \text{MHz}$

$C_q^{Cu} = q_{zz}51.69227\ \text{MHz}$

$C_q^{Ca} = q_{zz}(46.9930 \pm 23.4965)\ \text{MHz}$ or $\underline{-q_{zz}9.58657\ \text{MHz}}$

$C_q^{Cl} = q_{zz}(19.26712\ \text{MHz}[^{35}\text{Cl}]\ \text{and}\ 15.17873\ \text{MHz}\ [^{37}\text{Cl}])$

$C_q^{S} = -q_{zz}15.0378\text{MHz}$ or $\underline{-q_{zz}15.930620\ \text{MHz}}$

$C_q^{Al} = q_{zz}35.00977\ \text{MHz}$ or $\underline{q_{zz}32.96558\text{MHz}}$

$C_q^{Mg} = q_{zz}51.6923\ \text{MHz}$ or $\underline{q_{zz}46.852\ \text{MHz}}$

$C_q^{Na} = q_{zz}28.19578\ \text{MHz}$ or $\underline{q_{zz}25.23523\text{MHz}}$

$C_q^{O} = -q_{zz}6.10909\ \text{MHz}$

$C_q^{N} = q_{zz}3.75944\ \text{MHz}$

$C_q^{Be} = q_{zz}12.21817\ \text{MHz}$

$C_q^{Li} = -q_{zz}10.57342\ \text{MHz}$ or $\underline{-q_{zz}9.422092\text{MHz}}$

$C_q^{H} = q_{zz}641.4542\ \text{KHz}$ or $\underline{q_{zz}672.000\ \text{KHz}}$

Some useful ratios:

$Q(^{37}\text{Cl})/Q(^{35}\text{Cl}) = 0.7880983$

$Q(^{40}\text{K})/Q(^{39}\text{K}) = 1.244$

$Q(^{65}\text{Cu})/Q(^{63}\text{Cu}) = 0.9268$

Slide material courtesy of Paul Ellis

QUADRUPOLAR HAMILTONIAN

CARTESIAN COORDINATES:

$$H_Q = \frac{eQ}{6I(2I-1)\hbar}\hat{I}\cdot\tilde{V}\cdot\hat{I}$$

$$H_Q = \frac{eQ}{6I(2I-1)\hbar}\sum_{\substack{i,j= \\ x,y,z}} V_{ij}\left[\frac{3}{2}\left(\hat{I}_i\hat{I}_j + \hat{I}_j\hat{I}_i\right) - \delta_{ij}\hat{I}^2\right] =$$

$$\frac{e^2qQ}{4I(2I-1)\hbar}\left[3\hat{I}_Z^{2\,PAS} - \hat{I}^2 + \eta_Q\left(\hat{I}_x^{2\,PAS} - \hat{I}_y^{2\,PAS}\right)\right]$$

$$eq = V_{ZZ}^{PAS};\ \ \eta_Q = \frac{V_{XX}^{PAS} - V_{YY}^{PAS}}{V_{ZZ}^{PAS}};$$

$$C_Q = \frac{e^2qQ}{h}$$ **Quadrupole coupling constant**

QUADRUPOLAR HAMILTONIAN

CARTESIAN COORDINATES, LABORATORY FRAME:

$$\hat{H}_0 = -\omega_0 \hat{I}_Z; \qquad \begin{pmatrix} \hat{I}_X \\ \hat{I}_Y \\ \hat{I}_Z \end{pmatrix} = R(\theta,\phi) \begin{pmatrix} \hat{I}_X^{PAS} \\ \hat{I}_Y^{PAS} \\ \hat{I}_Z^{PAS} \end{pmatrix}$$

$$\hat{H}_Q = \frac{e^2qQ}{4I(2I-1)\hbar}\{\frac{1}{2}\left(3\cos^2\theta - 1\right)\left(3\hat{I}_Z^2 - \hat{I}^2\right)$$

$$+\frac{3}{2}\sin\theta\cos\theta\left[\hat{I}_Z\left(\hat{I}_+ + \hat{I}_-\right) + \left(\hat{I}_+ + \hat{I}_-\right)\hat{I}_Z\right] + \frac{3}{4}\sin^2\theta\left(\hat{I}_+^2 + \hat{I}_-^2\right)\}$$

$$+\eta_Q \frac{e^2qQ}{4I(2I-1)\hbar}\{\frac{1}{2}\cos 2\phi\left(1 - \cos^2\theta\right)\left(3\hat{I}_Z^2 - \hat{I}^2\right)$$

$$+\left(\cos^2\theta + 1\right)\left(\hat{I}_+^2 + \hat{I}_-^2\right)$$

$$+\frac{1}{2}\sin\theta[(\cos\theta\cos 2\phi - i\sin 2\phi)\left(\hat{I}_+\hat{I}_Z + \hat{I}_Z\hat{I}_+\right)$$

$$+(\cos\theta\cos 2\phi + i\sin 2\phi)\left(\hat{I}_-\hat{I}_Z + \hat{I}_Z\hat{I}_-\right)]$$

$$+(i/4)\sin 2\phi\cos\theta\left(\hat{I}_+^2 - \hat{I}_-^2\right)$$

QUADRUPOLAR HAMILTONIAN: HIGH FIELD LIMIT

H_Q TREATED BY PERTURBATION THEORY, ONLY FIRST AND SECOND ORDER TERMS ARE SIZEABLE IN MOST OF THE CASES

USE SPHERICAL COORDINATES:

$$\hat{H}_Q^{(1)} = \frac{e^2qQ}{4I(2I-1)}\sqrt{6}V_{20}\hat{T}_{20}$$

$$\hat{H}_Q^{(2)} = \frac{C_Q^2}{\omega_L}\sum_{m\neq 0}\frac{V_{2m}V_{2-m}\left[T_{2m},T_{2-m}\right]}{2m}$$

$$\begin{aligned}\hat{H}_Q^{(2)} = -\left(\frac{e^2qQ}{4I(2I-1)\hbar}\right)^2\frac{1}{\omega_L}\frac{2}{5}\times\Big\{&\left[-3\sqrt{10}\hat{T}_{30}+\hat{T}_{10}\left(3-4I(I+1)\right)\right]V_{00}\\ &+\left[-12\sqrt{10}\hat{T}_{30}-\hat{T}_{10}\left(3-4I(I+1)\right)\right]V_{20}\\ &+\left[-34\sqrt{10}\hat{T}_{30}+3\hat{T}_{10}\left(3-4I(I+1)\right)\right]V_{40}\Big\}\end{aligned}$$

ELECTRIC FIELD GRADIENT (EFG) TENSOR: CARTESIAN COORDINATES

SYMMETRIC, TRACELESS SECOND-RANK TENSOR, V

$$V_{XX} + V_{YY} + V_{ZZ} = 0$$

PRINCIPAL COMPONENTS OF THE EFG TENSOR:

$$|V_{ZZ}| \geq |V_{YY}| \geq |V_{XX}|$$

NUCLEAR QUADRUPOLE COUPLING CONSTANT:

$$C_Q = \frac{V_{ZZ}(eQ)}{h}, \ Q - electric \ quadrupole \ moment$$

ASYMMETRY PARAMETER:

$$\eta_Q = \frac{V_{XX} - V_{YY}}{V_{ZZ}}; \ 0 \leq \eta_Q \leq 1$$

ELECTRIC FIELD GRADIENT (EFG) TENSOR: SPHERICAL COORDINATES

SYMMETRIC, TRACELESS SECOND-RANK TENSOR:

5 components, $R_{2,m}$, where m = -2, -1, 0, 1, 2

PRINCIPAL AXIS SYSTEM WHERE TENSOR IS DIAGONAL:

$$\left\langle V_{2,\pm 1}^{PAS} \right\rangle = 0; \qquad \left| \left\langle V_{2,0}^{PAS} \right\rangle \right| > \left| \left\langle V_{2,\pm 2}^{PAS} \right\rangle \right|$$

NUCLEAR QUADRUPOLE COUPLING CONSTANT:

$$C_Q = 2\frac{eQ}{h}\left\langle V_{2,0}^{PAS} \right\rangle$$

ASYMMETRY PARAMETER:

$$\eta_Q C_Q = 2\sqrt{6}\frac{eQ}{h}\left\langle V_{2,\pm 2}^{PAS} \right\rangle$$

ELECTRIC FIELD GRADIENT (EFG) TENSOR: POINT CHARGE MODEL

EFG TENSOR IS DETERMINED BY THE COMBINED ELECTRONIC AND NUCLEAR WAVEFUNCTION, NO ANALYTICAL EXPRESSION IN THE GENERAL CASE

THE SIMPLEST APPROXIMATION: CLASSICAL POINT CHARGE MODEL

$$\langle V_{2,k} \rangle = \sum_{i=1}^{n} \frac{Z_i e}{d_i^3} \sqrt{\frac{4\pi}{5}} Y_{2,k}(\theta_i, \phi_i)$$

ATOMS CONTRIBUTING TO THE EFG TENSOR ARE TREATED AS POINT CHARGES, THE RESULTING EFG TENSOR IS THE SUM WITH RESPECT TO ALL ATOMS

VERY CRUDE MODEL, WORKS QUANTITATIVELY ONLY IN SIMPLEST IONIC SYSTEMS, BUT YIELDS QUALITATIVE TRENDS AND GENERAL UNDERSTANDING OF THE SYMMETRY AND MAGNITUDE OF THE EXPECTED TENSOR

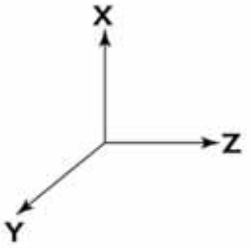
ELECTRIC FIELD GRADIENT (EFG) TENSOR: POINT CHARGE MODEL

$$\langle V_{2,k} \rangle = \sum_{i=1}^{n} \frac{Z_i e}{d_i^3} \sqrt{\frac{4\pi}{5}} Y_{2,k}(\theta_i, \phi_i)$$

Linear, one-coordinate:

$\theta = 0$, $\phi = 0$

$$\langle V_{2,0} \rangle = \frac{Ze}{d^3};\ \langle V_{2,\pm1} \rangle = 0;\ \langle V_{2,\pm2} \rangle = 0$$



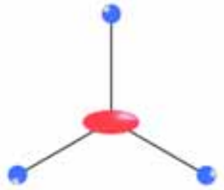
Linear, two-coordinate:

$\theta_1 = 0$, $\phi_1 = 0$; $\theta_2 = \pi$, $\phi_2 = 0$

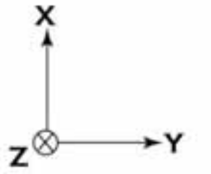
$$\langle V_{2,0} \rangle = \frac{2Ze}{d^3};\ \langle V_{2,\pm1} \rangle = 0;\ \langle V_{2,\pm2} \rangle = 0$$

Trigonal planar:

$\theta_1 = \pi/2$, $\phi_1 = 0$; $\theta_2 = \pi/2$, $\phi_2 = 2\pi/3$; $\theta_3 = \pi/2$, $\phi_3 = -2\pi/3$

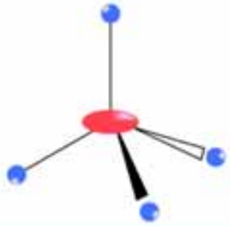


$$\langle V_{2,0} \rangle = -\frac{3}{2}\frac{Ze}{d^3};\ \langle V_{2,\pm1} \rangle = 0;\ \langle V_{2,\pm2} \rangle = 0$$



Tetrahedral:

$\theta_1 = 0$, $\phi_1 = 0$; $\theta_2 = 2\pi/3$, $\phi_2 = 0$; $\theta_3 = 2\pi/3$, $\phi_3 = 2\pi/3$; $\theta_4 = 2\pi/3$, $\phi_4 = -2\pi/3$



$$\langle V_{2,0} \rangle = 0;\ \langle V_{2,\pm1} \rangle = 0;\ \langle V_{2,\pm2} \rangle = 0$$

NMR OF QUADRUPOLES:
ENERGY LEVELS

FIRST-ORDER CORRECTION:

$$E_m^1 = \langle m | H_Q | m \rangle$$

SECOND-ORDER CORRECTION:

$$E_m^2 = \frac{\langle m | H_Q | n \rangle \langle n | H_Q | m \rangle}{E_m - E_n}$$

NMR OF QUADRUPOLES: ENERGY LEVELS

FIRST-ORDER CORRECTION:

$$E_m^1 = \frac{e^2qQ}{4I(2I-1)}(I(I+1)-3m^2)[\frac{1}{2}(3\cos^2\theta-1)$$

$$-\eta_Q\cos 2\phi(\cos^2\theta-1)]$$

SECOND-ORDER CORRECTION:

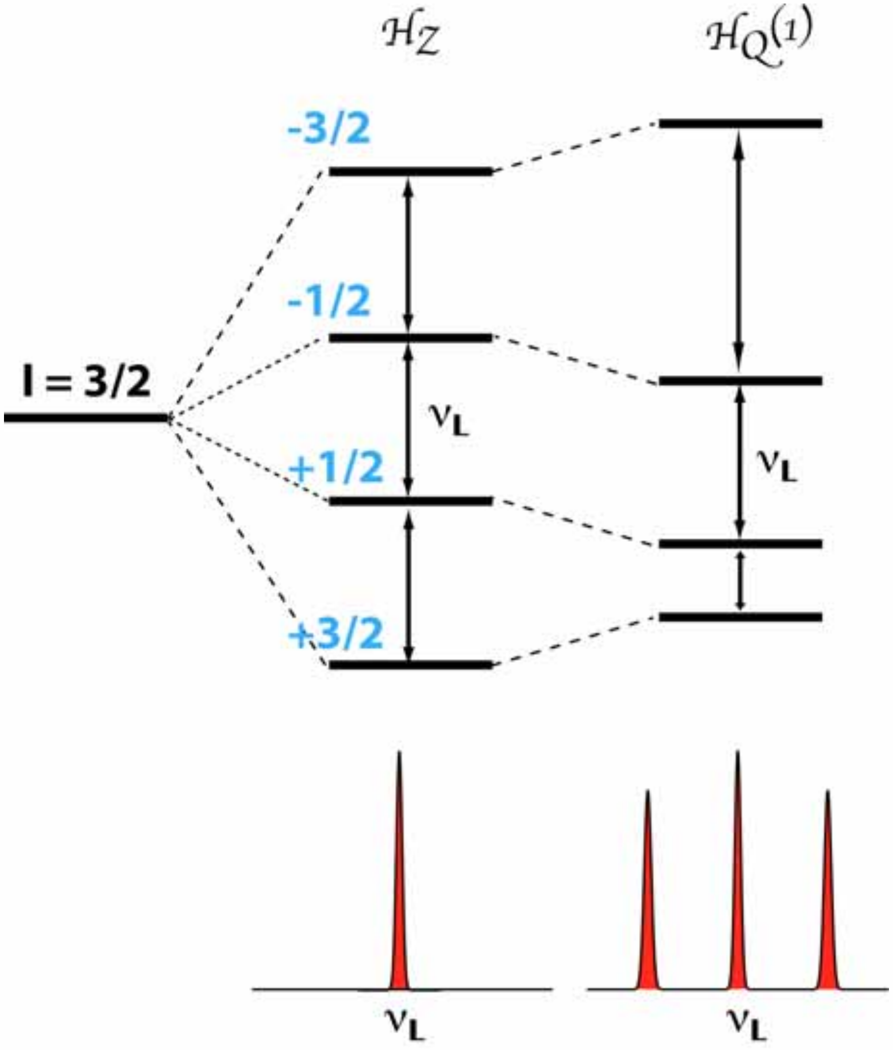
$$E_m^{(2)} = -\left(\frac{e^2qQ}{4I(2I-1)}\right)^2\frac{m}{\omega_L}\{-\frac{1}{5}(I(I+1)-3m^2)(3+\eta_Q^2)+$$

$$\frac{1}{28}(8I(I+1)-12m^2-3)((\eta_Q^2-3)(3\cos^2\theta-1)+6\eta_Q\sin^2\theta\cos 2\phi)$$

$$+\frac{1}{8}(18I(I+1)-34m^2-5)[\frac{1}{140}(18+\eta_Q^2)(35\cos^4\theta-30\cos^2\theta+3)$$

$$+\frac{3}{7}\eta_Q\sin^2\theta(7\cos^2\theta-1)\cos 2\phi+\frac{1}{4}\eta_Q^2\sin^4\theta\cos 4\phi]\}$$

ENERGY LEVELS IN THE PRESENCE OF QUADRUPOLAR INTERACTION



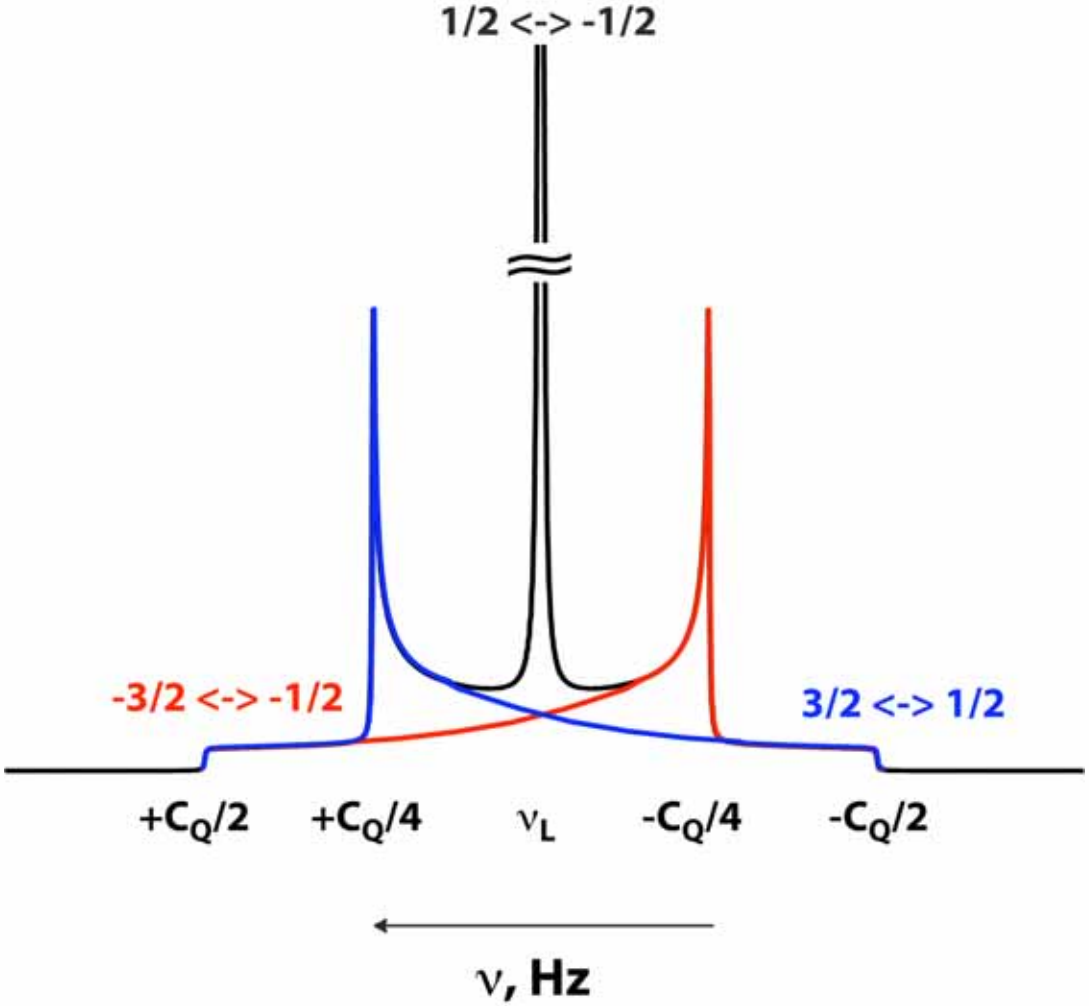
Single crystal

Central transition unaffected
by first-order quadrupolar interaction

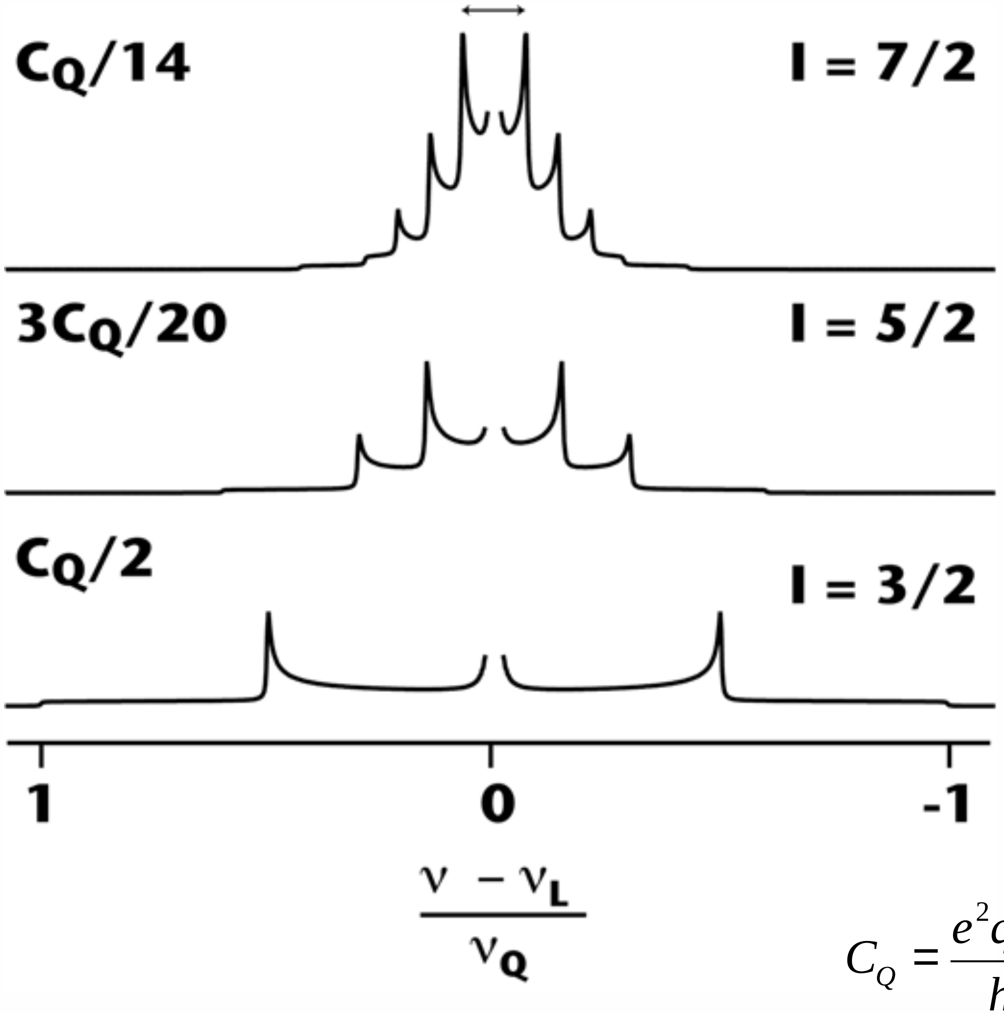
Central transition: 1/2 - -1/2
Satellite transitions: 3/2 - 1/2, -3/2 - -1/2

QUADRUPOLAR POWDER PATTERNS

SPIN-3/2 NUCLEUS; FIRST-ORDER QUADRUPOLAR INTERACTION

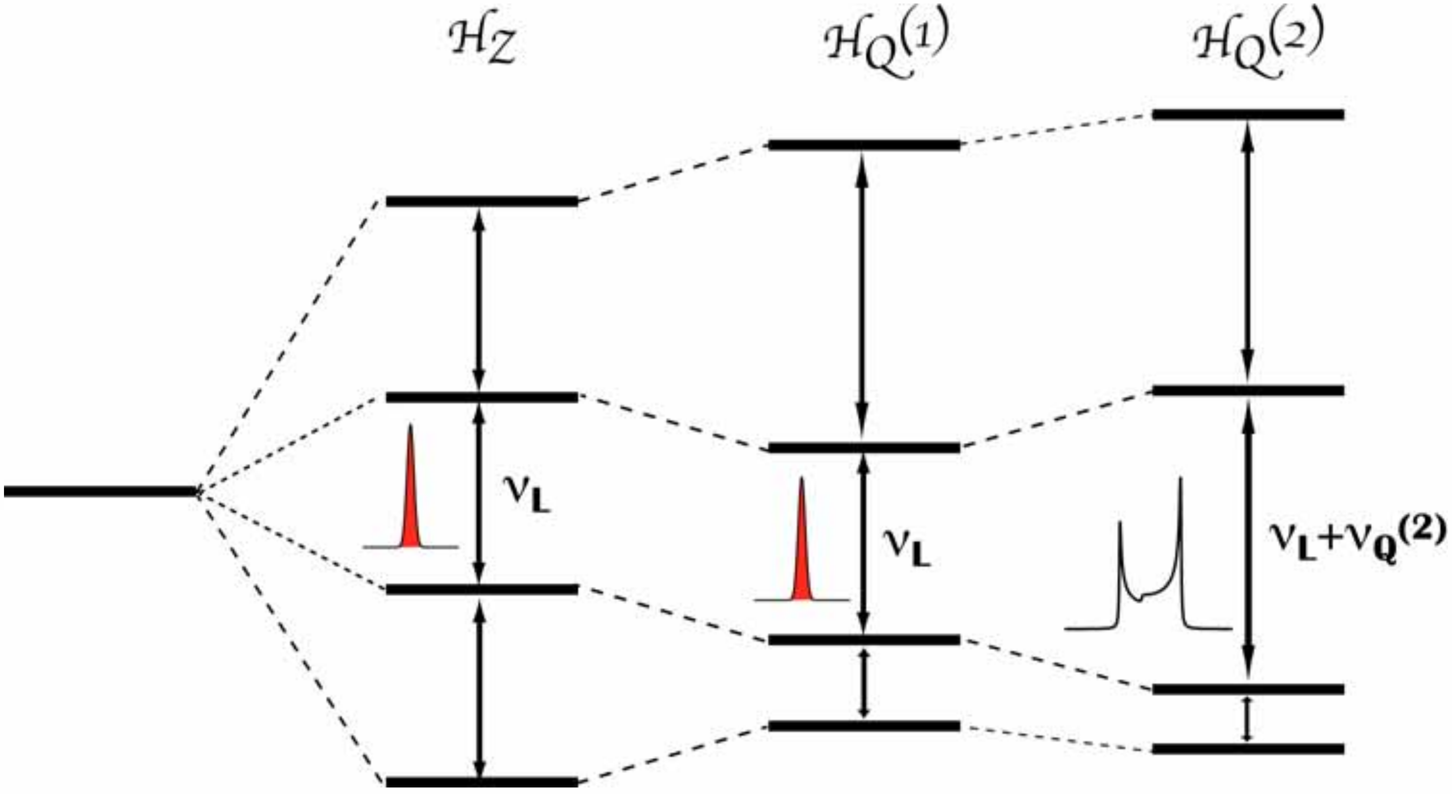


SATELLITE TRANSITIONS: FIRST ORDER BROADENING

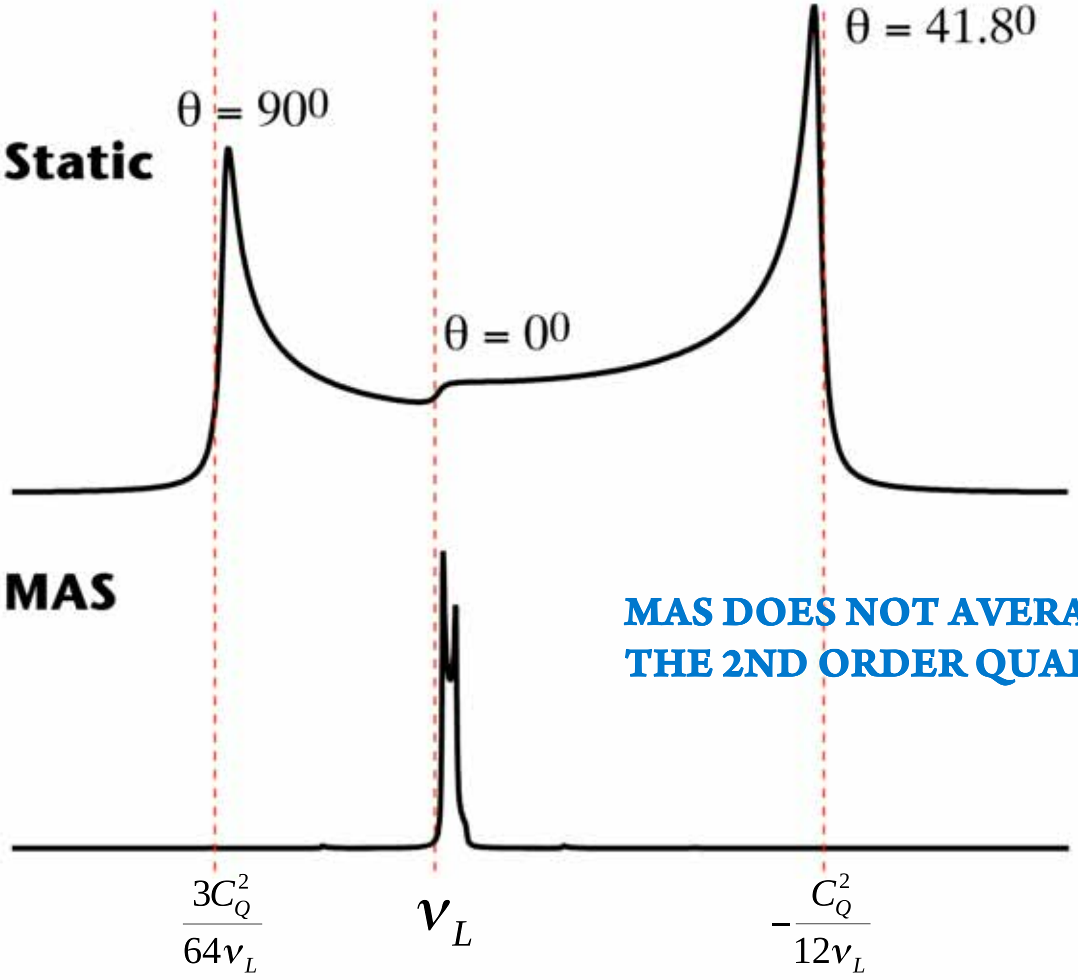


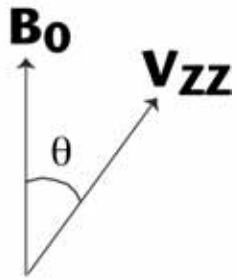
$$C_Q = \frac{e^2qQ}{h};\ \nu_Q = \frac{3C_Q}{2I(2I-1)}$$

SECOND-ORDER QUADRUPOLAR BROADENING: ENERGY LEVELS



SECOND-ORDER QUADRUPOLAR BROADENING: CENTRAL TRANSITION POWDER LINESHAPES





MAS DOES NOT AVERAGE OUT
THE 2ND ORDER QUADRUPOLAR BROADENING

SECOND-ORDER QUADRUPOLAR SHIFTS AND BROADENING

SECOND ORDER QUADRUPOLE SHIFTS FOR THE (m, m-1) TRANSITION RELATIVE TO THE CHEMICAL SHIFT IN A POWDER SAMPLE:

$$\Delta\nu_{m,m-1} = -\frac{3}{40}\left(\frac{C_Q^2}{\nu_L}\right)\left\{\frac{I(I+1)-9m(m-1)-3}{I^2(2I-1)^2}\right\}\left(1+\frac{\eta^2}{3}\right)$$

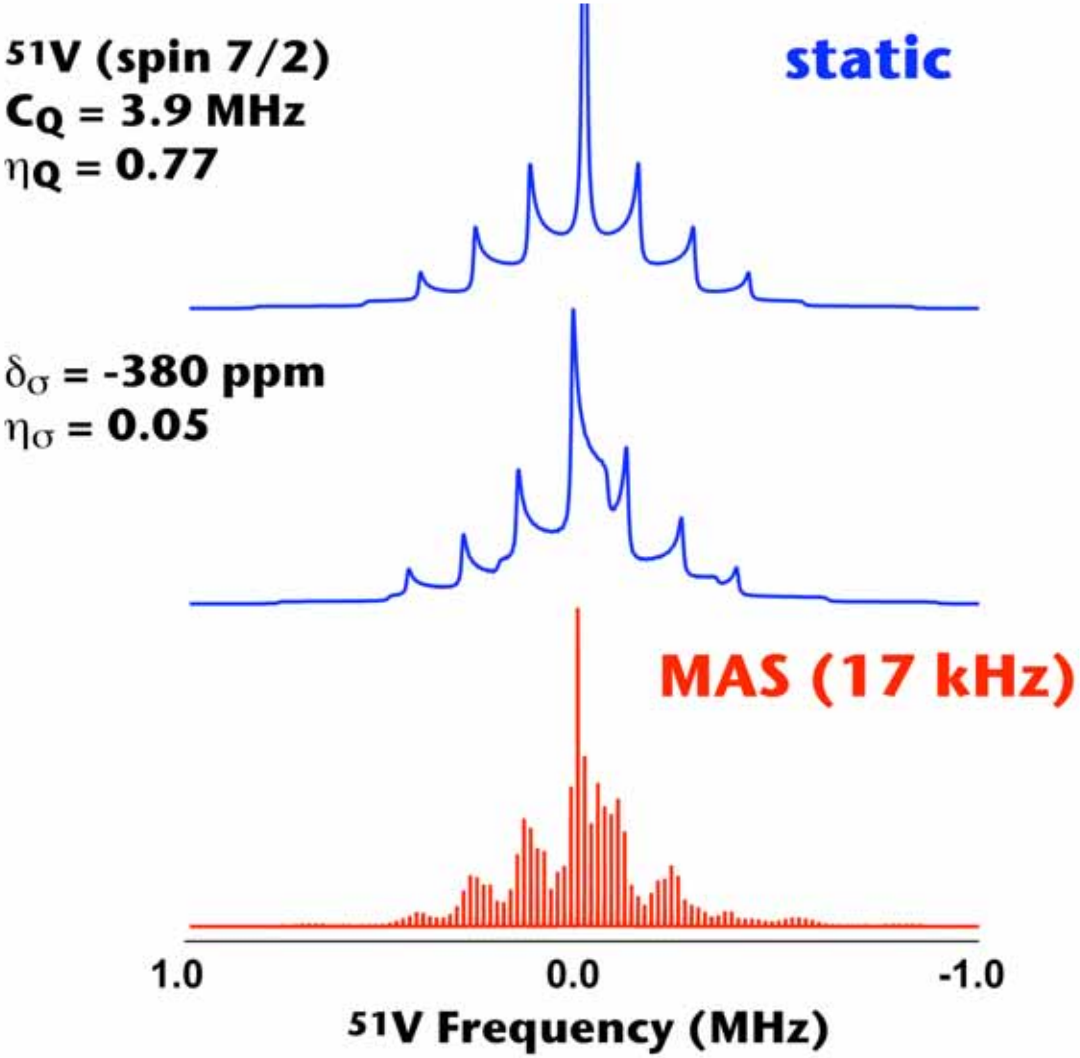
A. Samoson, Chem. Phys. Lett 119: 29 (1985)

SECOND ORDER QUADRUPOLE BROADENING OF SATELLITE TRANSITIONS RELATIVE TO THE CENTRAL TRANSITION WITH FAST MAS:

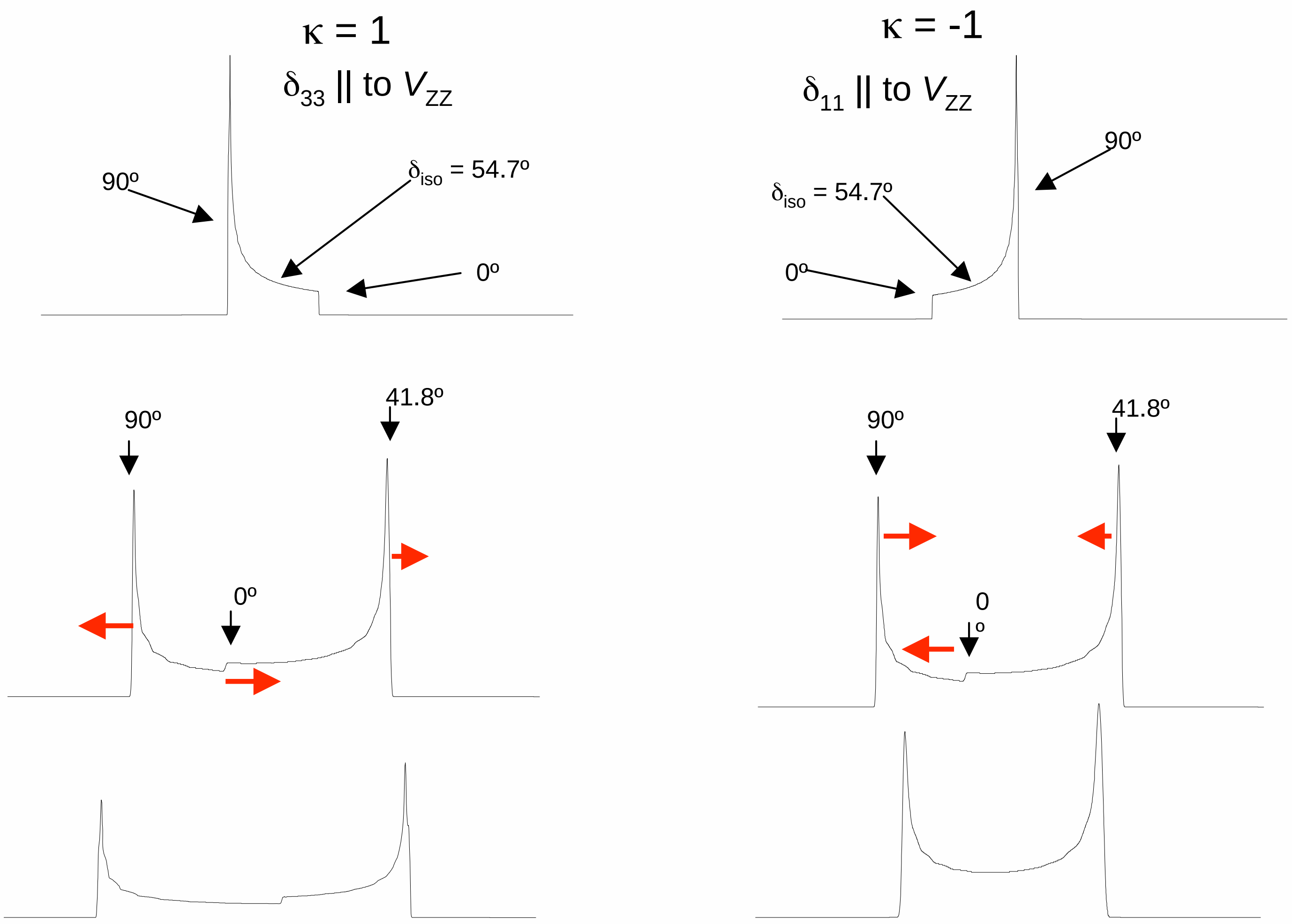
$$\frac{\Delta(m,m-1)}{\Delta\left(\frac{1}{2},-\frac{1}{2}\right)} = \frac{6I(I+1)-34m(m-1)-13}{6I(I+1)-\frac{9}{2}}$$

SATELLITE TRANSITIONS ARE BROADENED TO DIFFERENT EXTENTS

QUADRUPOLAR LINESHAPES IN THE PRESENCE OF CSA

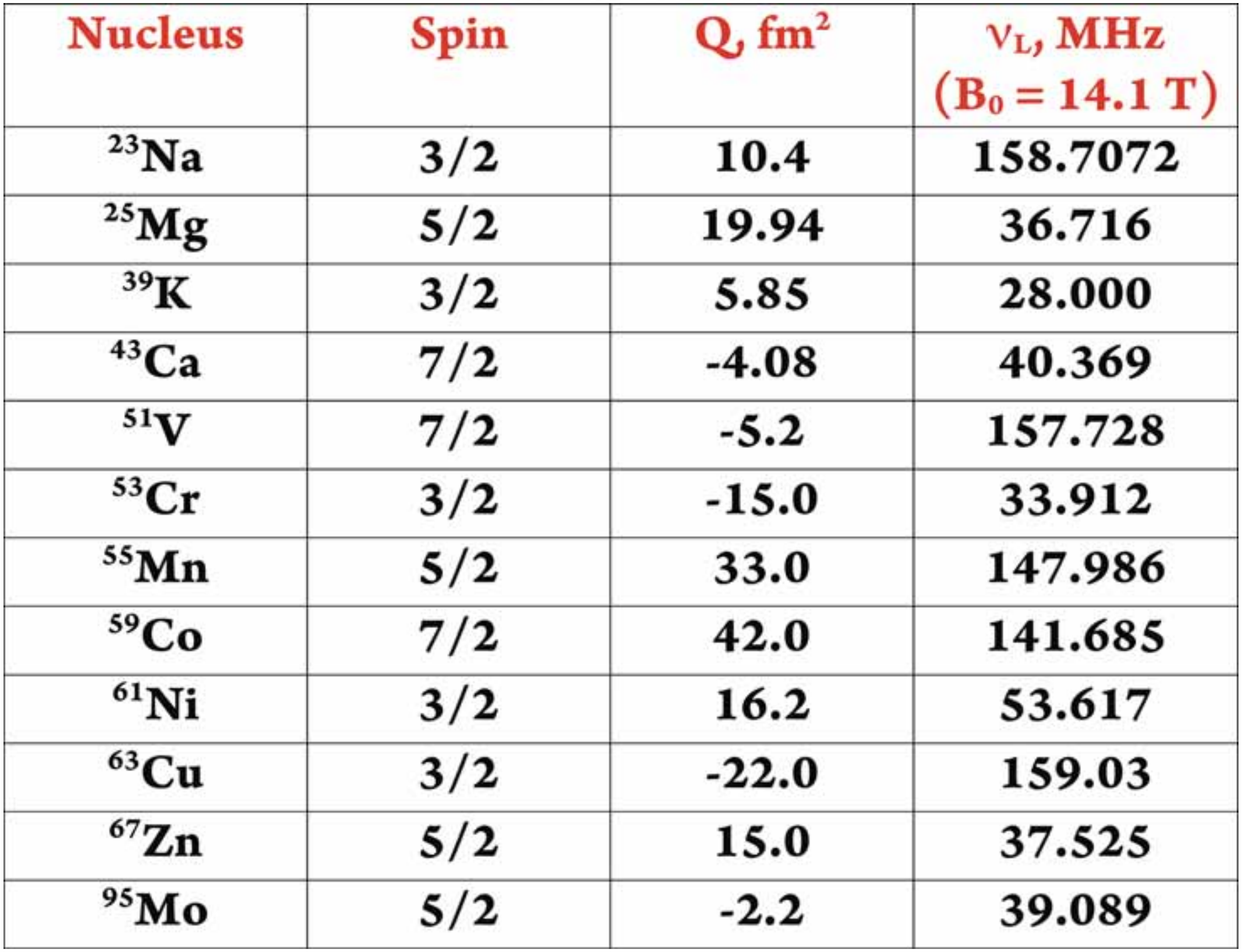


SECOND ORDER QUADRUPOLAR LINESHAPES IN THE PRESENCE OF CSA



(figure courtesy of Kris Ooms)

PROPERTIES OF SOME QUADRUPOLAR METALS

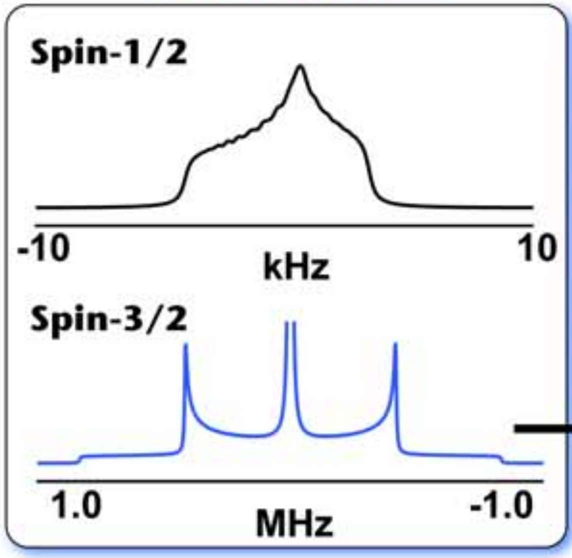


Nucleus	Spin	Q, fm^2	ν_L, MHz (B_0 = 14.1 T)
^{23}Na	3/2	10.4	158.7072
^{25}Mg	5/2	19.94	36.716
^{39}K	3/2	5.85	28.000
^{43}Ca	7/2	-4.08	40.369
^{51}V	7/2	-5.2	157.728
^{53}Cr	3/2	-15.0	33.912
^{55}Mn	5/2	33.0	147.986
^{59}Co	7/2	42.0	141.685
^{61}Ni	3/2	16.2	53.617
^{63}Cu	3/2	-22.0	159.03
^{67}Zn	5/2	15.0	37.525
^{95}Mo	5/2	-2.2	39.089

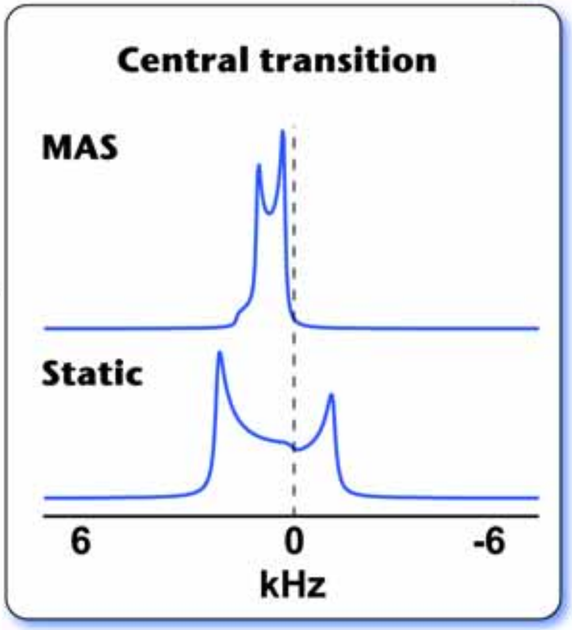
R. K. Harris, E. D. Becker, S. M. Cabral de Menezes, R. Goodfellow, and P. Granger, Pure Appl. Chem. 73: 1795 (2001)

NMR SPECTROSCOPY OF QUADRUPOLAR NUCLEI: CHALLENGES

I. Broad lines



II. MAS does not remove second-order broadenings



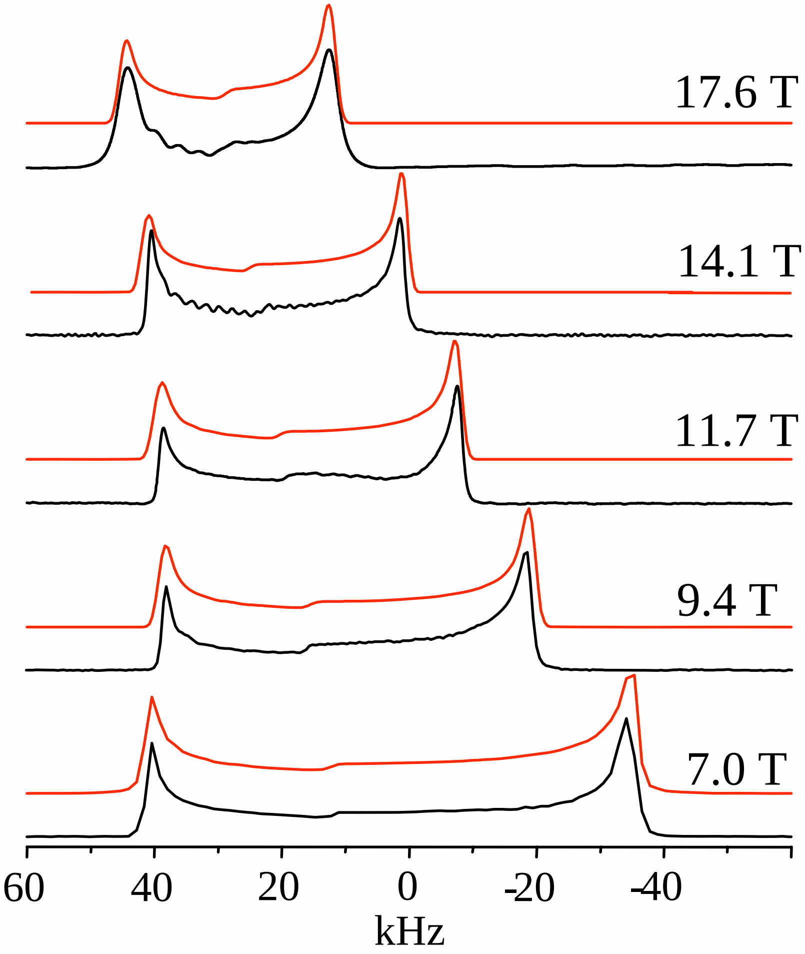
**III. Poor sensitivity (low γ,
low abundance,
low concentration in biomolecules)**

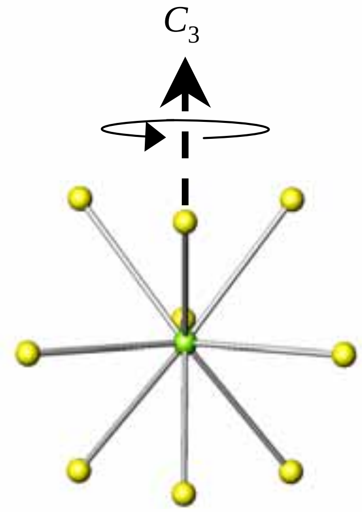
NMR SPECTROSCOPY OF QUADRUPOLAR NUCLEI: UNIVERSAL SOLUTIONS

1. **ULTRAHIGH MAGNETIC FIELDS**
2. **ULTRAHIGH MAGNETIC FIELDS**
3. **ULTRAHIGH MAGNETIC FIELDS**

NMR SPECTROSCOPY OF QUADRUPOLAR NUCLEI: FIELD STRENGTH DEPENDENCE

^{139}La (I=7/2) STATIC CENTRAL TRANSITION SSNMR SPECTRA OF $LaCl_3$





C_Q = 15.55 ± 0.05 MHz

η_Q = 0.0

δ_{iso} = 305 ± 5 ppm

Ω = 50 ± 10 ppm

κ = 1.0

β = 0

K. J. Ooms, K. W. Feindel, M. J. Willans, R. E. Wasylishen, J. V. Hanna, K. J. Pike, M. E. Smith, SSNMR, 2005, 28, 125-134 (figure courtesy of Kris Ooms)

NMR SPECTROSCOPY OF QUADRUPOLAR NUCLEI: AFFORDABLE SOLUTIONS

(as of January 2008)

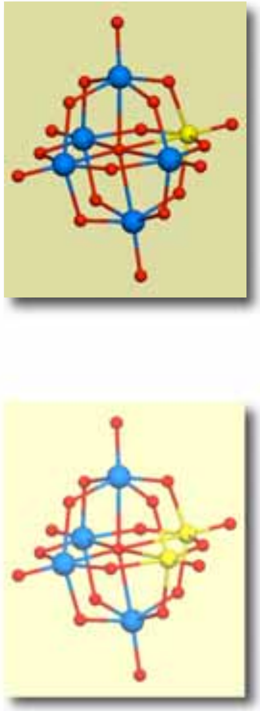
1. REASONABLY HIGH MAGNETIC FIELDS
2. SPATIAL AVERAGING TECHNIQUES
3. SPIN AVERAGING TECHNIQUES
4. SENSITIVITY ENHANCEMENT TECHNIQUES

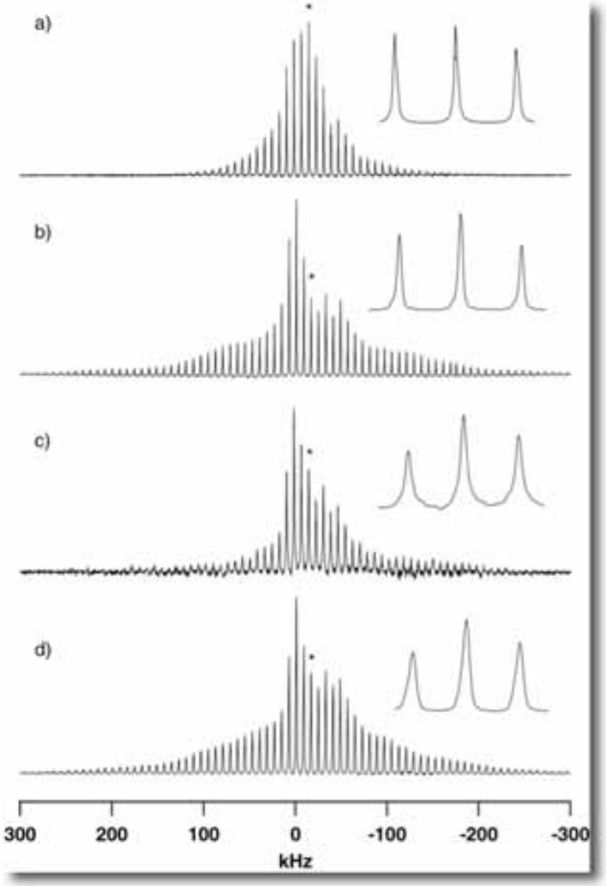
NMR SPECTROSCOPY OF QUADRUPOLAR METALS

1. **LET'S START WITH SIMPLE EXAMPLES**

DETECTING SPECTRA OF QUADRUPOLAR NUCLEI: SMALL AND MODERATE C_Q

^{51}V (I=7/2) SSNMR SPECTRA OF V-SUBSTITUTED POLYOXOTUNGSTATES: single pulse, central and satellite transitions





C_Q = 0.650 MHz; η_Q = 0.65
δ_σ = 200 ppm; η_σ = 1.0

C_Q = 1.3 MHz; η_Q = 0.8
δ_σ = 466 ppm; η_σ = 0.1

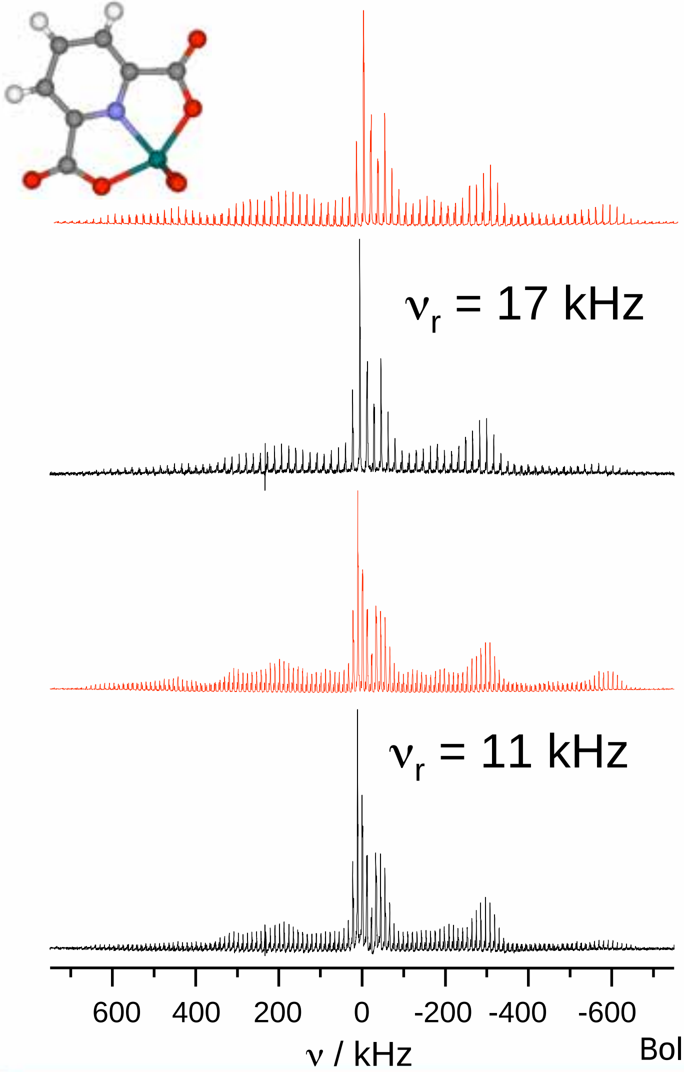
C_Q = 1.050 MHz; η_Q = 0.95
δ_σ = 418 ppm; η_σ = 0.1

C_Q = 1.56 MHz; η_Q = 0.35
δ_σ = 456 ppm; η_σ = 0.2

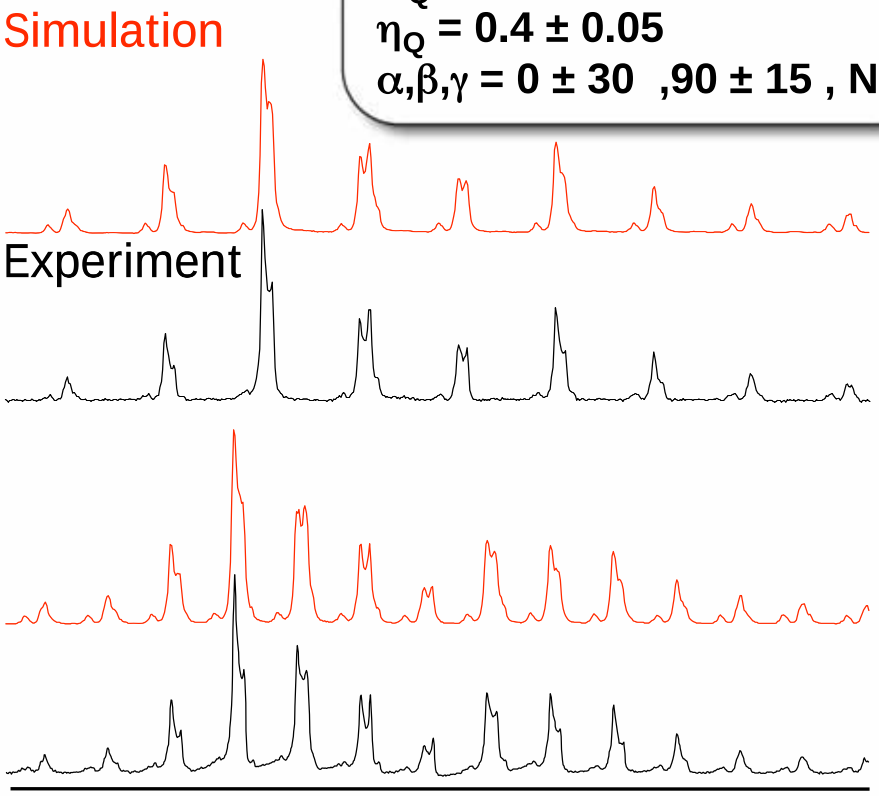
Huang, Todaro, Francesconi, Polenova (2003) J. Am. Chem. Soc. 125, 5928-5938

DETECTING SPECTRA OF QUADRUPOLAR NUCLEI: SMALL AND MODERATE C_Q

^{51}V (I=7/2) SSNMR SPECTRA OF $NH_4(VO)_2$-dipicolinic acid derivative



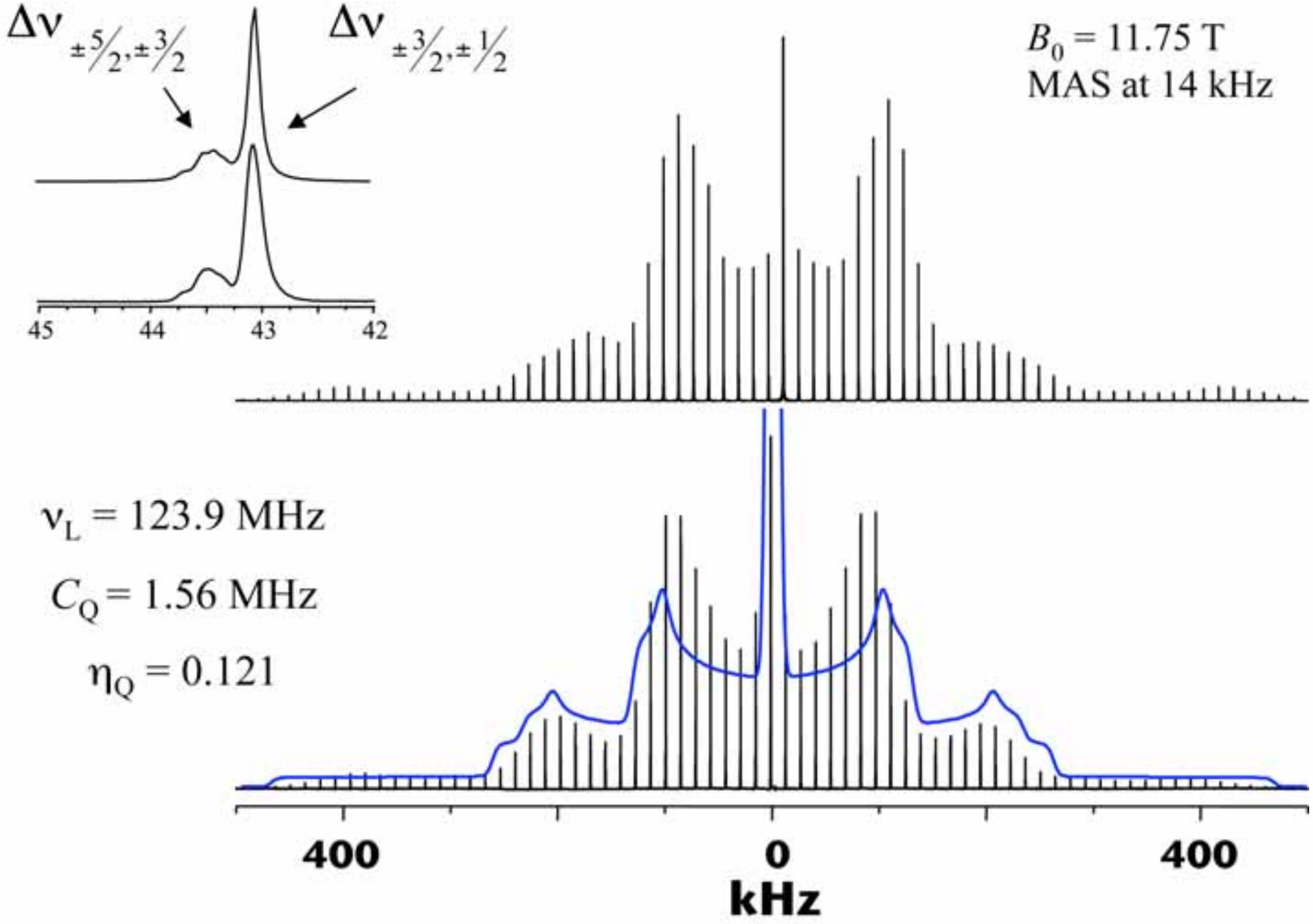
δ_{iso} = -110 ± 3 ppm
Ω = 825 ± 30 ppm
κ = 1.0 ± 0.1
C_Q = 5.8 ± 0.2 MHz
η_Q = 0.4 ± 0.05
α,β,γ = 0 ± 30 ,90 ± 15 , NA



Bolte, Ooms, Baruah, Smee, Crans, Polenova (2008 in press) J. Chem. Phys.

DETECTING SPECTRA OF QUADRUPOLAR NUCLEI: SMALL AND MODERATE C_Q

^{55}Mn (I=5/2) SSNMR SPECTRA OF $KMnO_4$

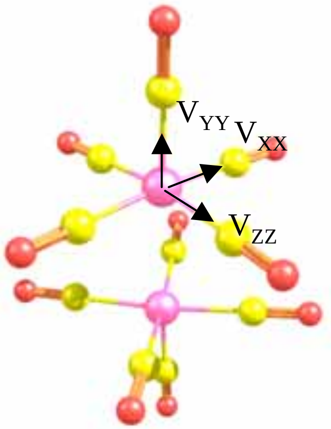


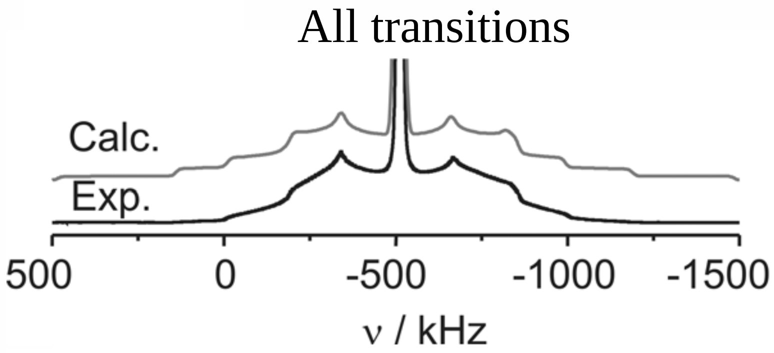
K. J. Ooms, R. E. Wasylishen (unpublished, figure courtesy of Kris Ooms)

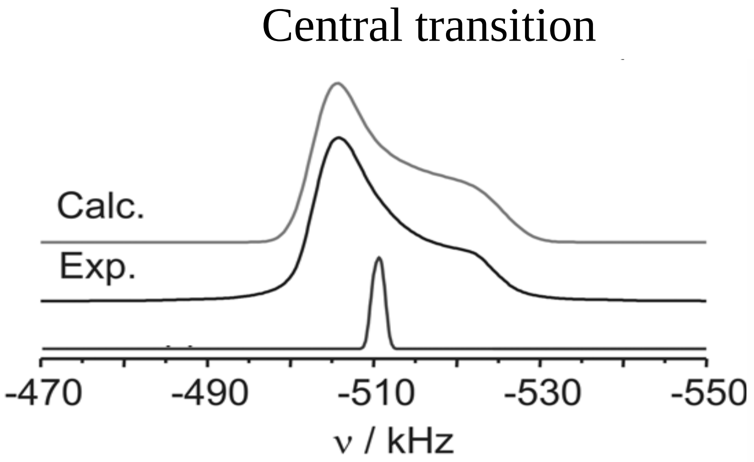
DETECTING SPECTRA OF QUADRUPOLAR NUCLEI: SMALL AND MODERATE C_Q

^{55}Mn (I=5/2) STATIC SPECTRA OF $Mn_2(CO)_{10}$

C_Q = 3.28 MHz
η_Q = 0.36
δ_{iso} = -2310 ppm
Ω = 105 ppm
κ = -0.95
α,β,γ = 90, 90, 0 º







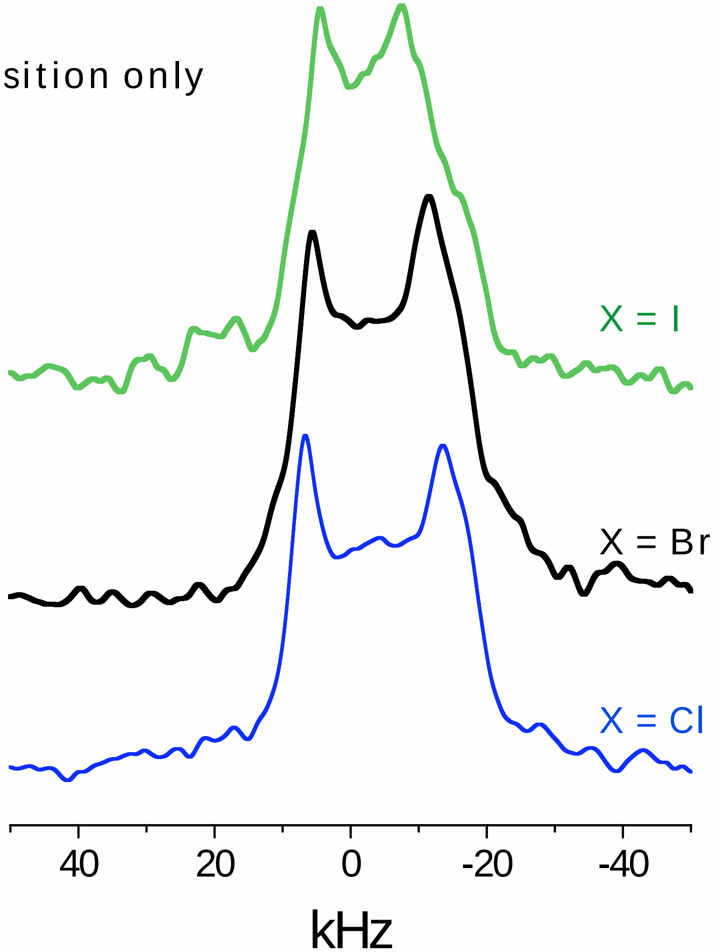
K. J. Ooms, K. W. Feindel, V. V. Terskikh, R. Wasylishen, Inorg. Chem. 2006, 45, 8492-8499 (cover article; figure courtesy of Kris Ooms)

NMR SPECTROSCOPY OF QUADRUPOLAR METALS

2. LET’S MOVE ON

DETECTING SPECTRA OF QUADRUPOLAR NUCLEI: LARGE C_Q

^{25}Mg (I=5/2) SSNMR SPECTRA OF LABELED Mg(15-crown-5)$(H_2O)_2X_2$



Static
Central transition only
B_0 = 17.6 T

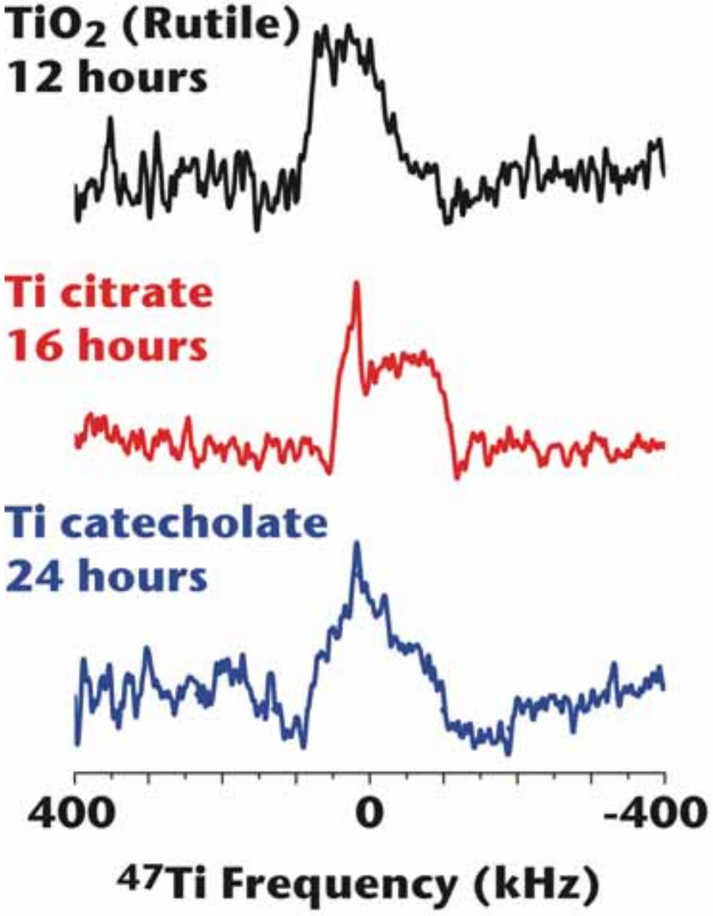
K. J. Ooms, R. E. Wasylishen (unpublished, figure courtesy of Kris Ooms)

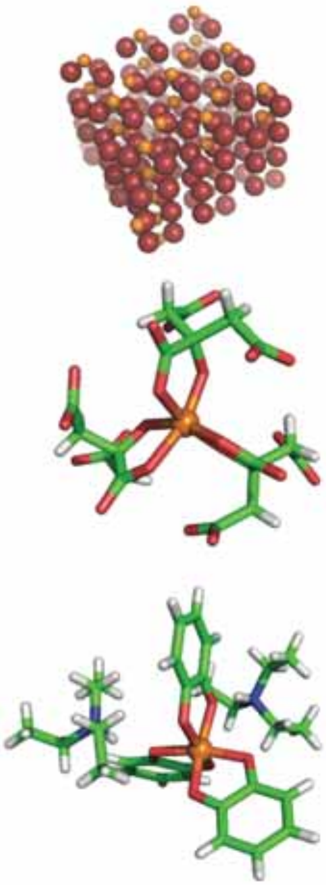
DETECTING SPECTRA OF QUADRUPOLAR NUCLEI: LARGE C_Q

^{47}Ti (I=5/2) STATIC ECHO CENTRAL TRANSITION SPECTRA OF LABELED Ti SOLIDS

B_0 = 14.1 T;

C_Q = 12 MHz
(DFT/b3lyp)



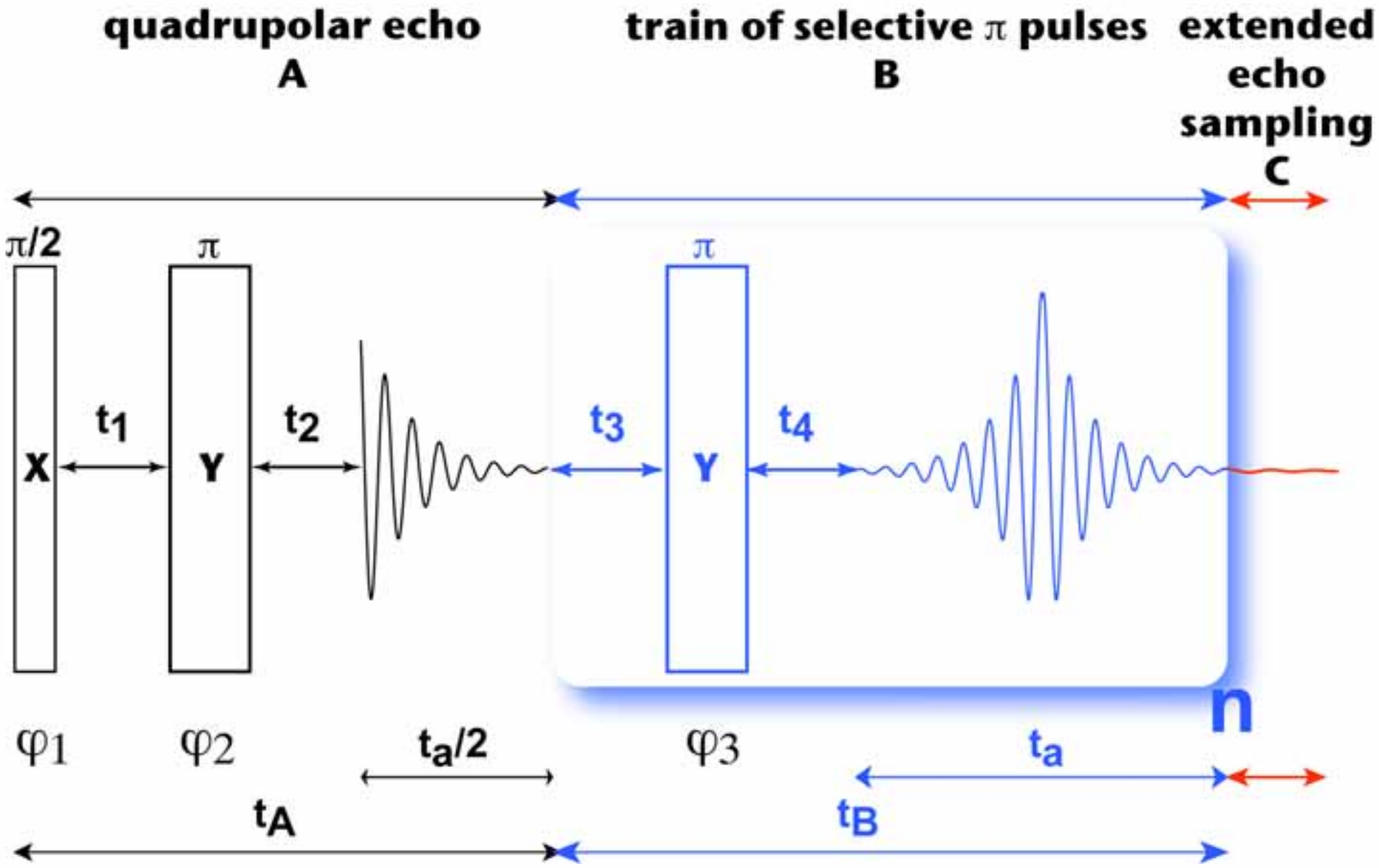


K. Ooms, S. Bolte, R. Uppal, A. Valentine, T. Polenova (unpublished)

NMR SPECTROSCOPY OF QUADRUPOLAR METALS WITH LOW RECEPTIVITY AND LARGE C_Q

3. NEED SENSITIVITY ENHANCEMENT

SENSITIVITY ENHANCEMENT IN QUADRUPOLES: QCPMG EXPERIMENT

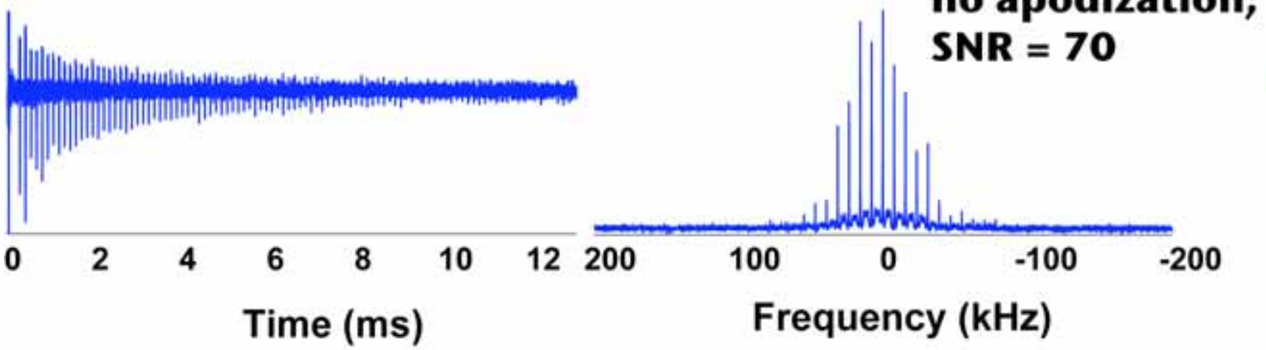


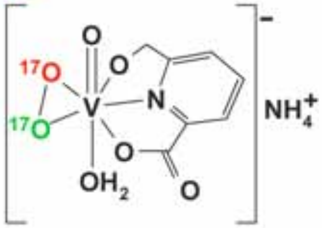
Static: J. T. Cheng and P. D. Ellis (1989), J. Phys. Chem., 93, 2549

QCPMG-MAS: F. H. Larsen, H. J. Jakobsen, P. D. Ellis, N. C. Nielsen (2000), J. Magn. Res., 131, 144

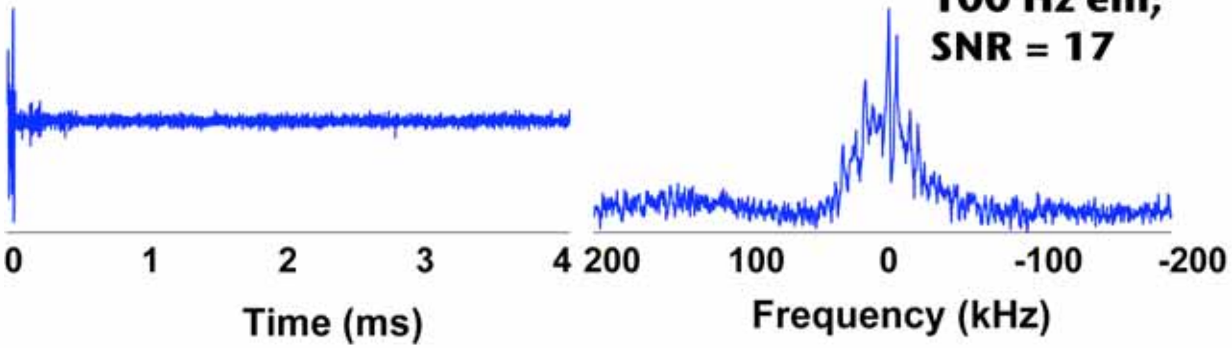
QCPMG-MAS EXPERIMENT: ^{17}O SPECTRA OF A PEROXO VANADIUM (V) COMPLEX

QCPMG-MAS (17 kHz), 122 k scans, experiment time: 17 hours


no apodization;
SNR = 70

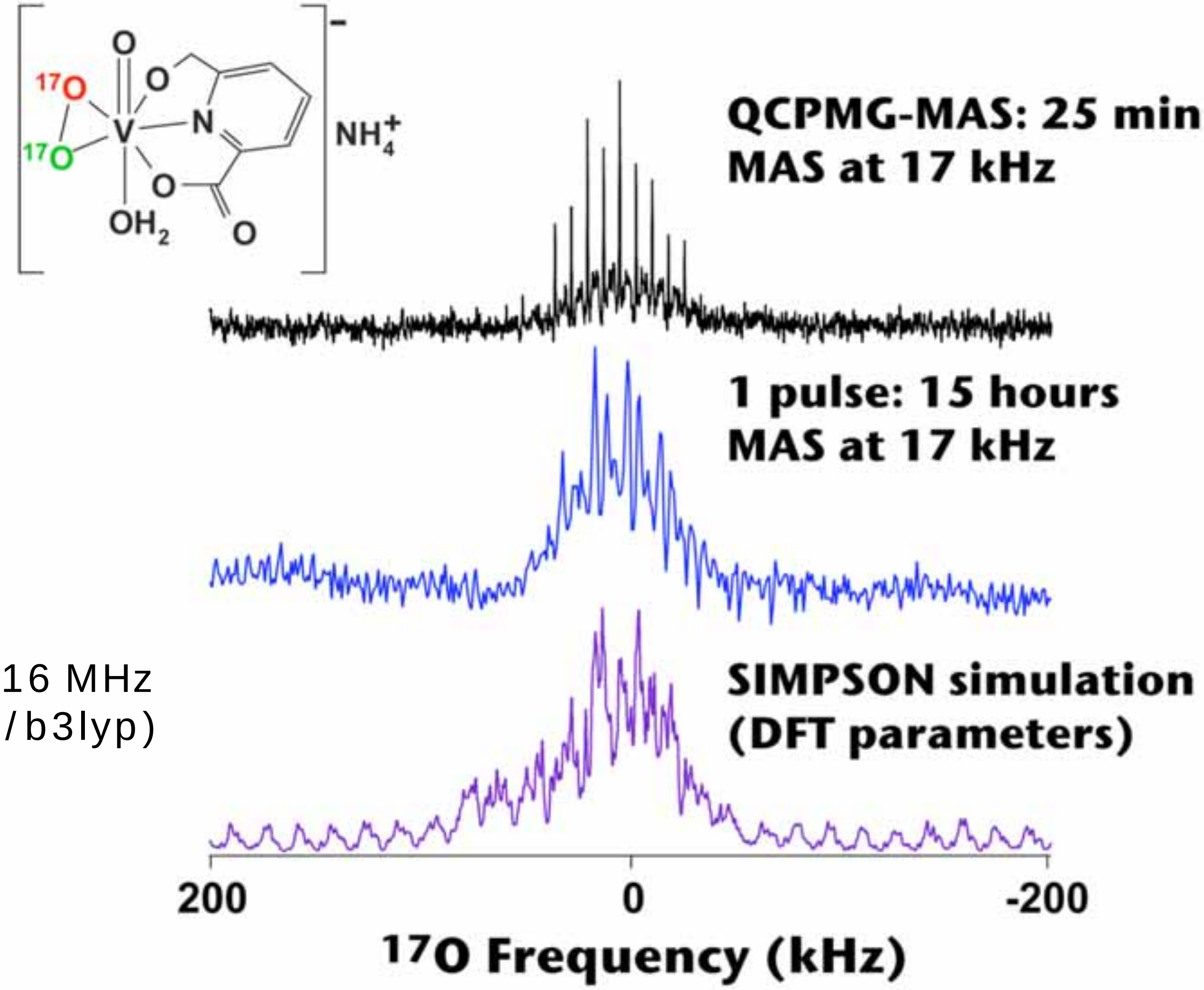


One pulse (17 kHz MAS), 315 k scans, experiment time: 26.2 hours


100 Hz em;
SNR = 17

N. Pooransingh-Margolis and T. Polenova (unpublished)

QCPMG-MAS EXPERIMENT: ^{17}O SPECTRA OF A PEROXO VANADIUM (V) COMPLEX

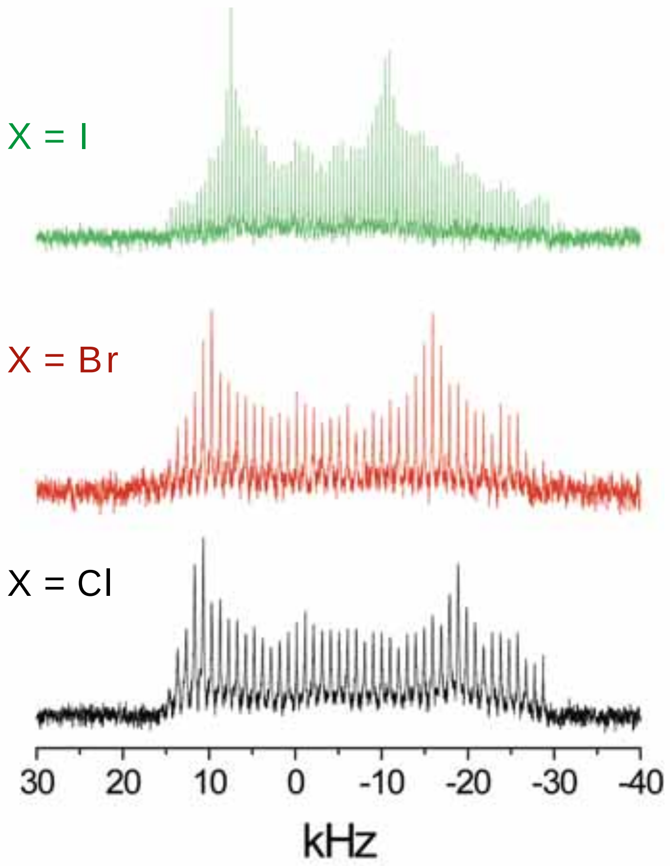


C_Q = 16 MHz
(DFT/b3lyp)

N. Pooransingh-Margolis and T. Polenova (unpublished)

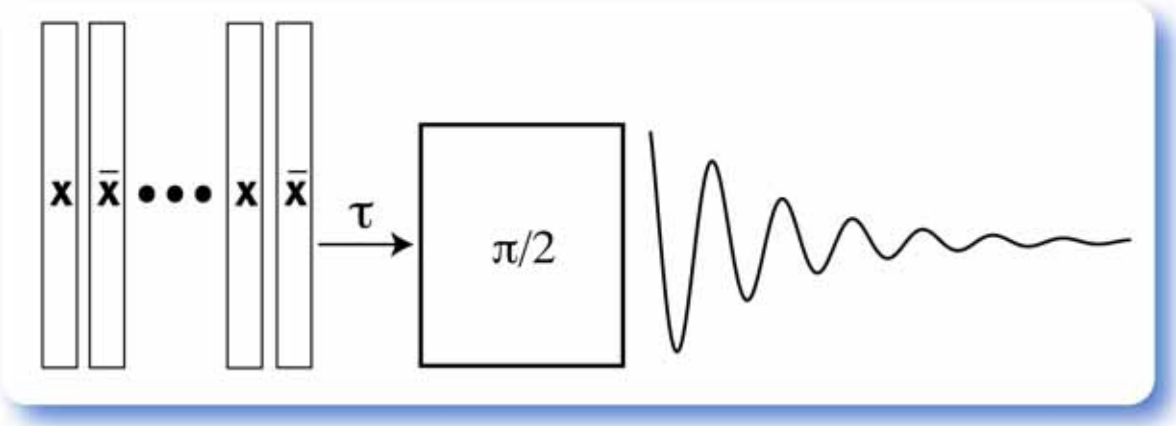
QCPMG EXPERIMENT: ^{25}Mg SPECTRA

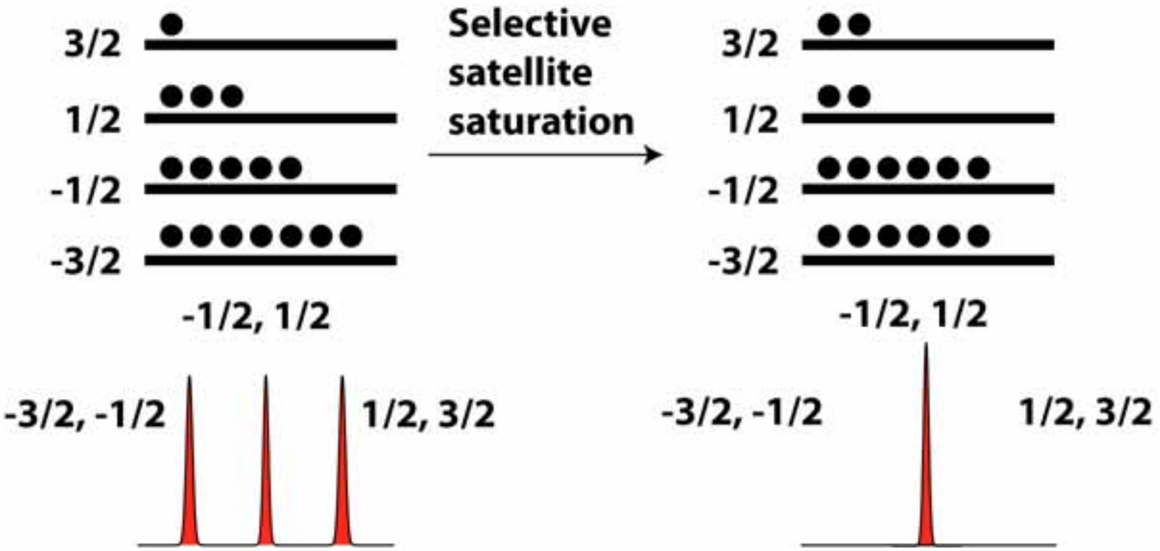
^{25}Mg (I=5/2) QCPMG SPECTRA OF LABELED Mg(15-crown-5)$(H_2O)_2X_2$



K. Ooms, R. Wasylishen (unpublished, figure courtesy of Kris Ooms)

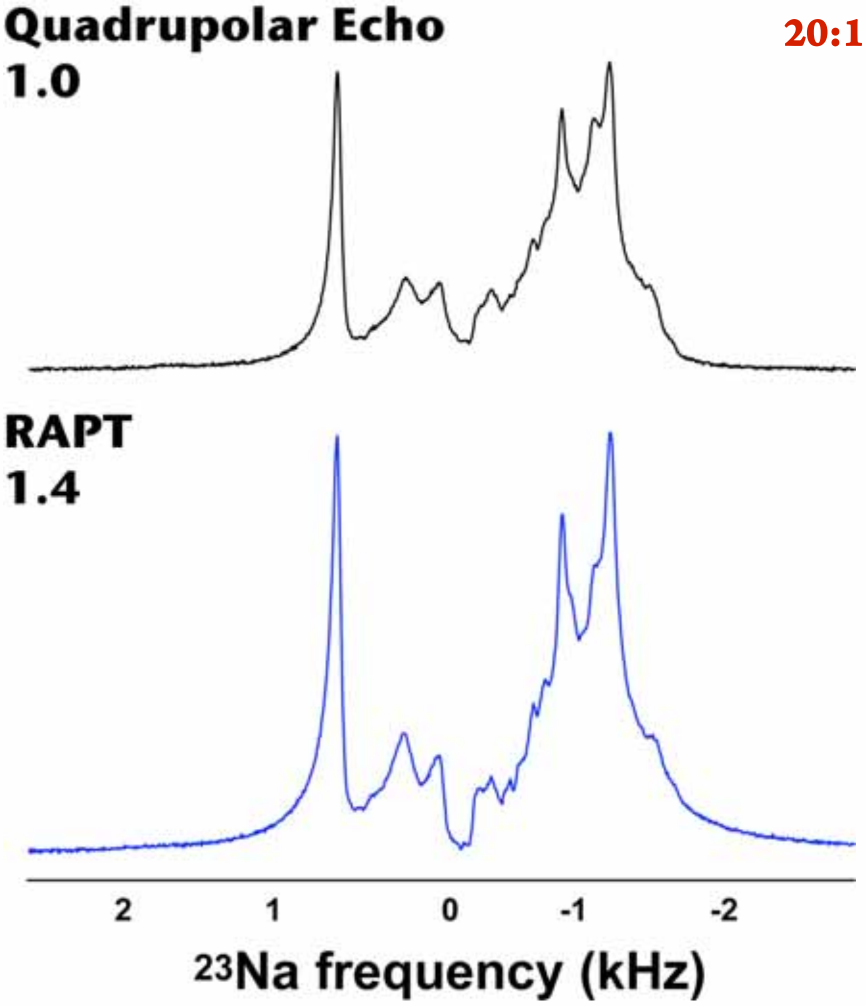
SENSITIVITY ENHANCEMENT IN QUADRUPOLES: RAPT EXPERIMENT





Z. Yao, H.-T. Kwak, D. Sakellariou, L. Emsley, P. J. Grandinetti (2000), Chem. Phys. Lett., 327, 85-90

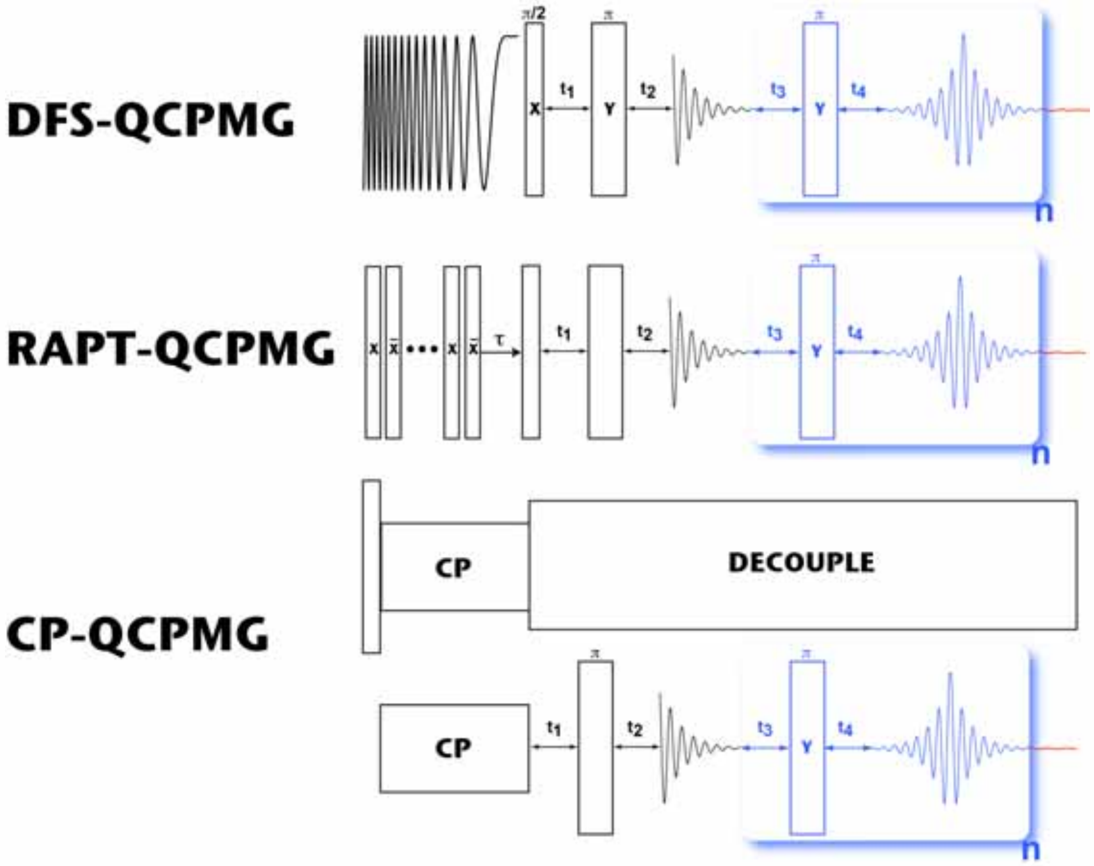
SENSITIVITY ENHANCEMENT IN QUADRUPOLES: COMPARISON FOR ^{23}Na



20:1 mixture of $Na_2C_2O_4$ and NaCl

N. Pooransingh-Margolis and T. Polenova

SENSITIVITY ENHANCEMENT IN QUADRUPOLES: MODIFIED QCPMG SEQUENCES

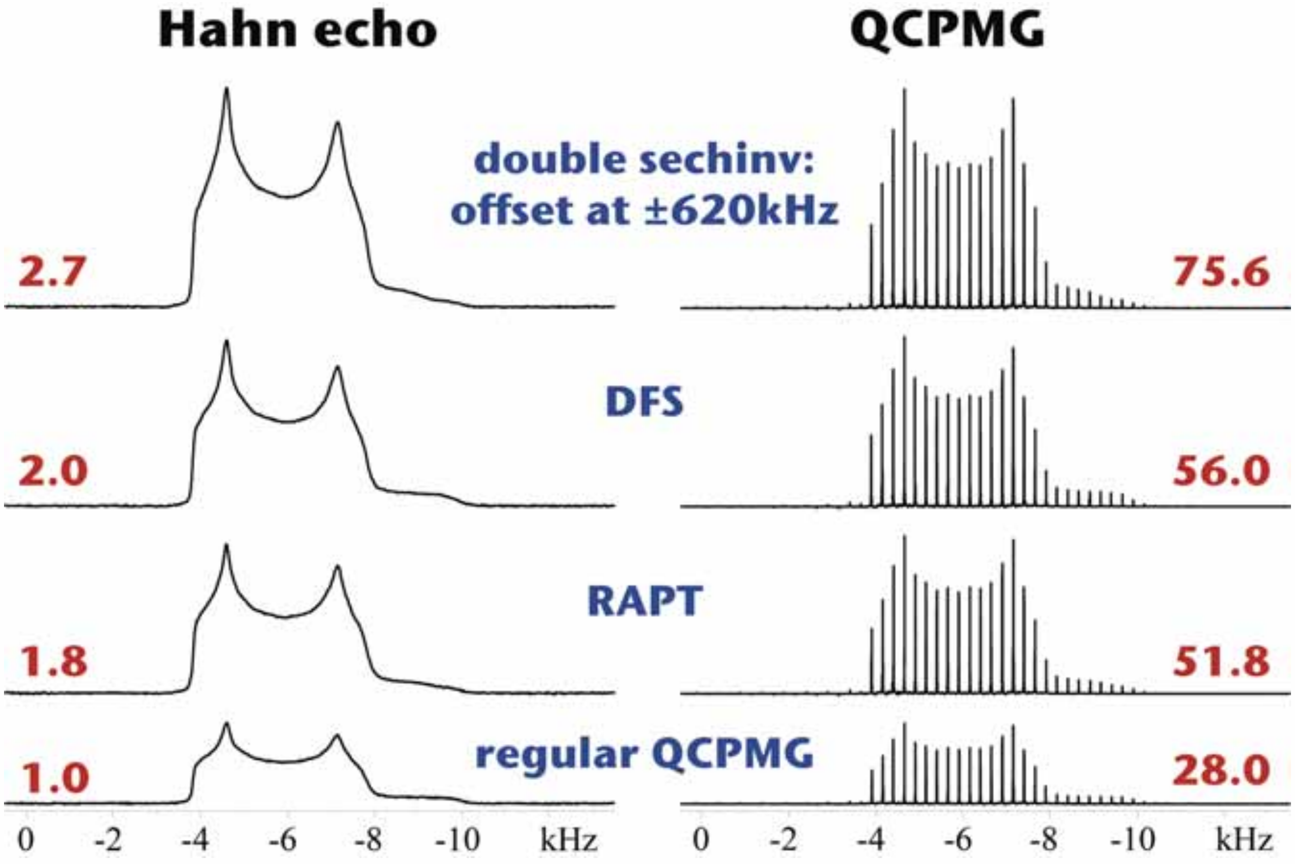


R. W. Schurko, I. Hung, and
C. M. Widdifield (2003)
Chem. Phys. Lett., 379, 1-10

I. Hung, A. J. Rossini, and
R. W. Schurko (2004)
J. Phys. Chem. A, 108, 7112-7120

DFS: Double Frequency Sweeps;
RAPT: Rotor Assisted Polarization Transfer
CP: Cross Polarization

SENSITIVITY ENHANCEMENT TECHNIQUES: COMPARISON FOR ^{87}Rb IN RbClO$_4$



R. Siegel, T. T. Nakashima, and R. E. Wasylishen, Chem. Phys. Lett., 2004, 388, 441-445;
Figure courtesy of Kris Ooms

NMR SPECTROSCOPY OF QUADRUPOLAR METALS

4. WHAT ABOUT RESOLUTION?

NMR SPECTROSCOPY OF QUADRUPOLAR METALS IN BIOLOGICAL SOLIDS

INTERESTING FACT:

IN METALLOPROTEINS, THERE IS TYPICALLY ONLY ONE OR VERY FEW METAL SITES PRESENT, AND RESOLUTION IS NOT SUCH AN ISSUE AS IN INORGANIC MATERIALS

THIS IS A LUXURY AND ALLOWS FOR RELATIVELY STRAIGHTFORWARD EXTRACTION OF NMR PARAMETERS FROM THE SPECTRA

OBVIOUSLY, THIS IS NOT THE CASE IN ION-BINDING PROTEINS, WHERE MULTIPLE SITES MAY BE PRESENT, SO ONE HAS TO WORRY ABOUT RESOLUTION

RESOLUTION ENHANCEMENT IN QUADRUPOLES

$$H^{(2)}_{diag} = \frac{\omega_L}{\omega_0}\left[a d^{(0)}_{0,0}(\beta) D^{(0)}_{0,0}(\Omega_{PAS})\rho^{\lambda}_{0,0} + a_2 d^{(2)}_{0,0}(\beta)\sum_{p=-2}^{2} D^{(2)}_{p,0}(\Omega_{PAS})\rho^{\lambda}_{2,p} + a_4 d^{(4)}_{0,0}\sum_{p=-4}^{4} D^{(4)}_{p,0}(\Omega_{PAS})\rho^{\lambda}_{4,p}\right] I_Z$$

Averaging of spherical harmonics Y_ℓ^m of different ranks under point subgroups of the full rotation group SO(3):

Rotation around a single axis is not sufficient for averaging rank 2 and 4 anisotropies

Symmetry

$\langle Y_{\ell m}\rangle = 0$

Tetragonal (D_4)

ℓ = 0 1 2 3 4 5 6 7 8 9 10

Tetrahedral (T)

ℓ = 0 1 2 3 4 5 6 7 8 9 10

Octahedral (O)

ℓ = 0 1 2 3 4 5 6 7 8 9 10

Icosahedral (I)

ℓ = 0 1 2 3 4 5 6 7 8 9 10

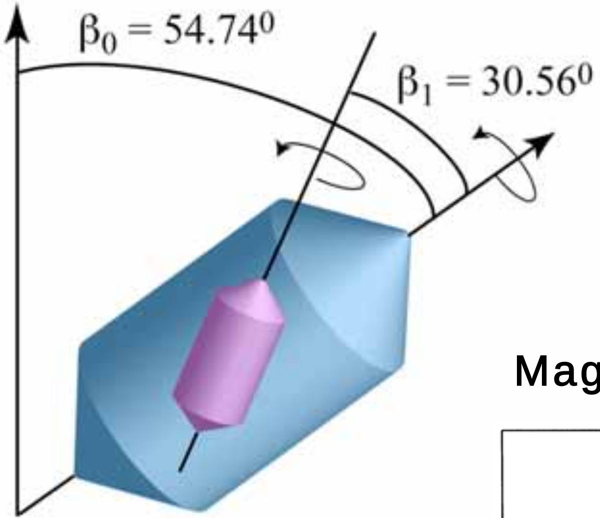
Rotation (SO(3))

ℓ = 0 1 2 3 4 5 6 7 8 9 10

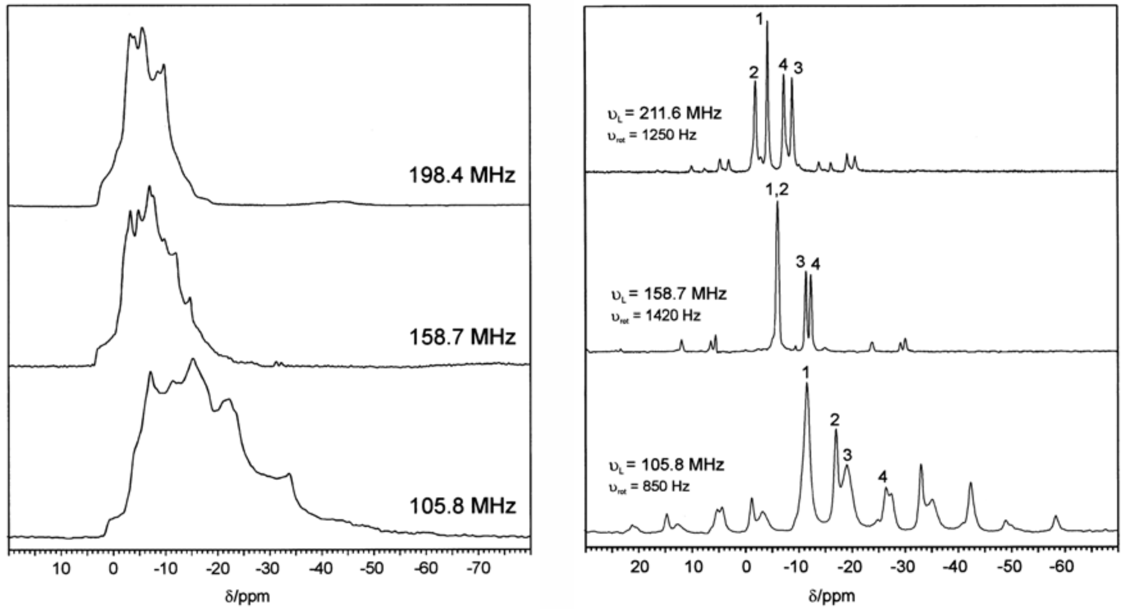
simultaneous averaging of rank-2 and 4 anisotropies

E. W. Wooten, K. T. Mueller, A. Pines (1992) Accts. Chem. Res. 25, 209

SPATIAL AVERAGING: DOUBLE ROTATION



^{23}Na MAS and DOR of $Na_4P_2O_7$

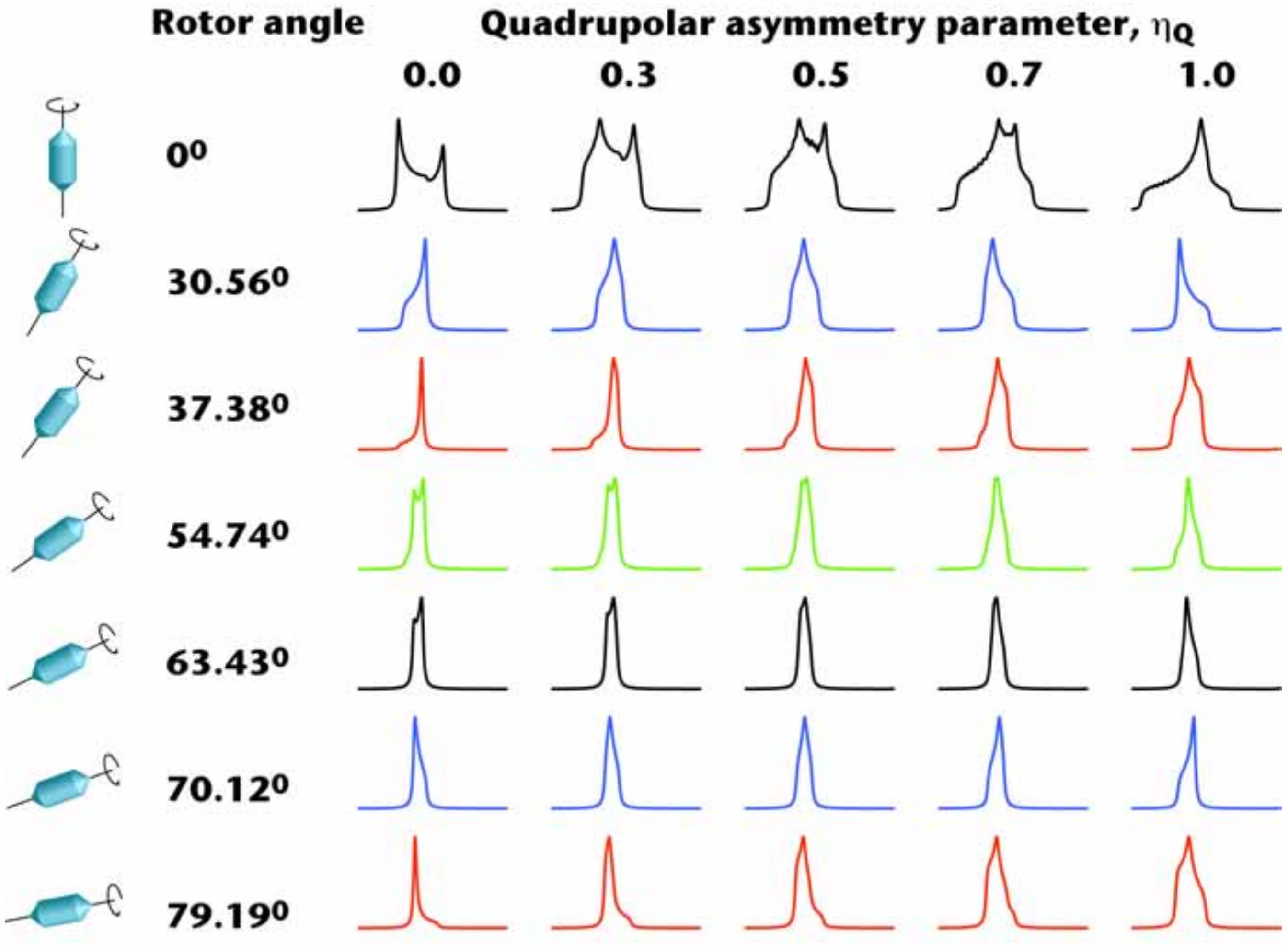


Magic Angle Spinning

Double Rotation

G. Engelhardt, A. P. M. Kentgens, H. Koller, A. Samoson (1999) Solid State NMR 15, 171-180

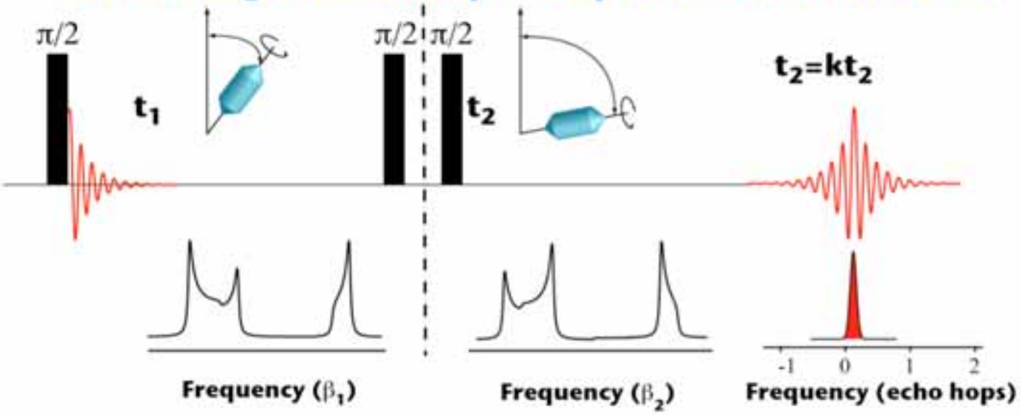
SPATIAL AVERAGING: QUADRUPOLAR LINESHAPES AT DIFFERENT ROTOR ANGLES



K. T. Mueller, Y. Wu, B. F. Chmelka, J. Stebbins, A. Pines (1991) J. Am. Chem. Soc. 113, 32-38

SPATIAL AVERAGING: DYNAMIC ANGLE SPINNING

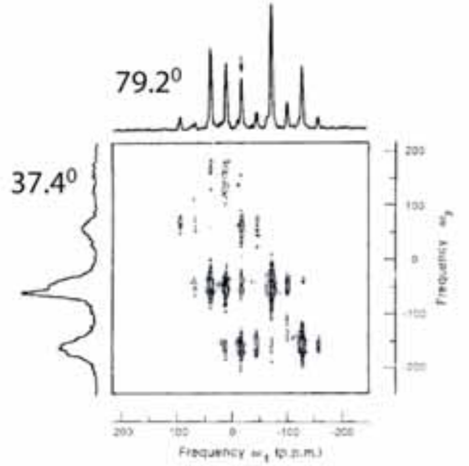
Refocusing of anisotropic frequencies with DAS echo



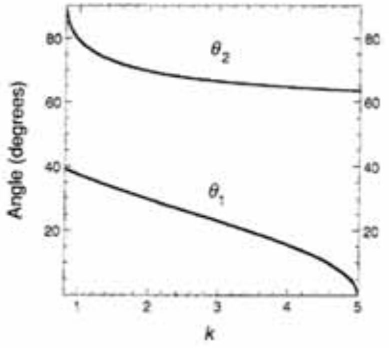
Pure phase absorption DAS spectra:

P. J. Grandinetti, J. H. Baltisberger, A. Llor, Y. K. Lee, U. Werner, M. A. Eastman, A. Pines (1993) J. Magn. Reson. A 103, 72-83

^{17}O DAS Spectra of Crystobalite SiO_2



Echo in t_2 at kt_1



Multiple pairs of rotor angles yield echoes

A. Llor, J. Virlet (1988) Chem. Phys. Lett. 152, 248-253

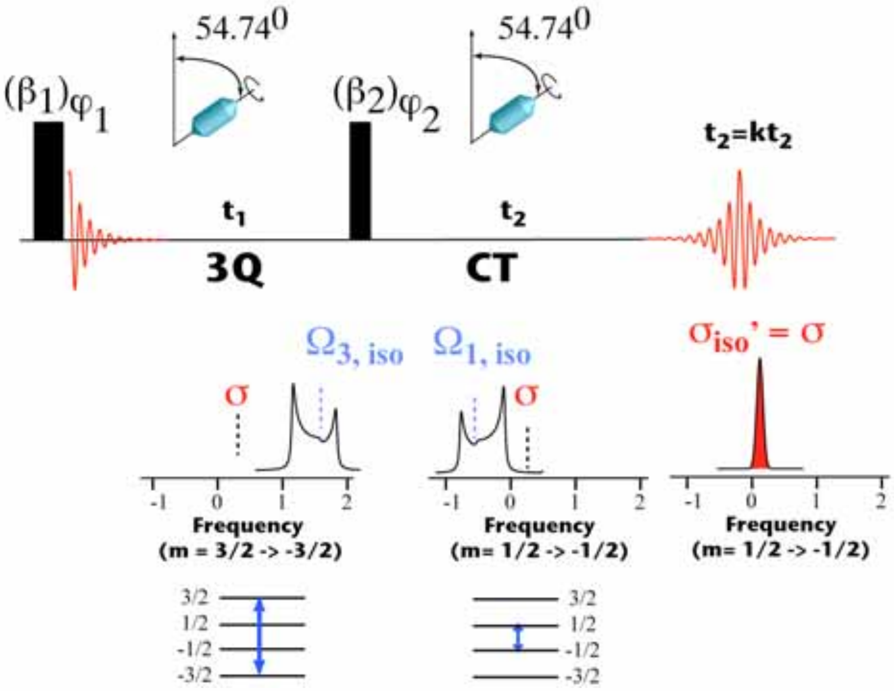
B. F. Chmelka, K. T. Mueller, A. Pines, J. Stebbins, Y. Wu, J. W. Zwanziger (1989) Nature 339, 42-43

K. T. Mueller, Y. Wu, B. F. Chmelka, J. Stebbins, A. Pines (1991) J. Am. Chem. Soc. 113, 32-38

P. J. Grandinetti (1995) Encyclopedia of Nuclear Magnetic Resonance, John Wiley and Sons

SPIN AVERAGING: THE MQMAS EXPERIMENT

Refocusing of anisotropic frequencies with MQMAS echo

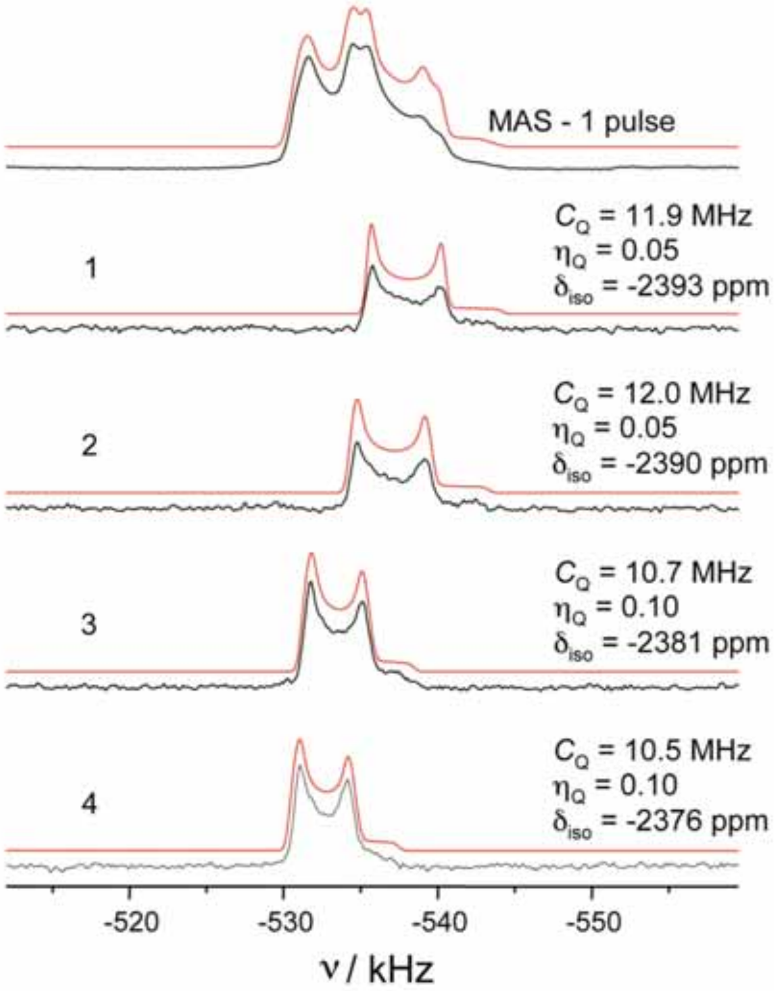


Spin	Transition (m → -m)	K
3/2	3QMAS	7/9
5/2	3QMAS	19/12
	5QMAS	25/12
7/2	3QMAS	101/45
	5QMAS	11/9
	7QMAS	161/45
9/2	3QMAS	91/36
	5QMAS	95/36
	7QMAS	7/18
	9QMAS	31/6

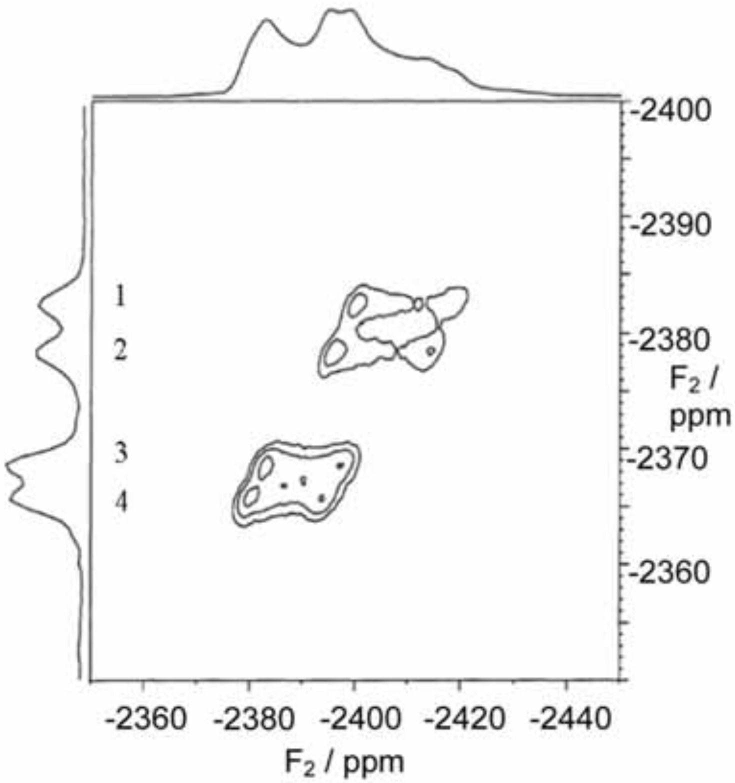
TRIPLE QUANTUM SPECTRUM IS A MIRROR IMAGE OF SQ SPECTRUM

L. Frydman and J. S. Harwood (1995), J. Am. Chem. Soc. 117, 5367
A. Medek, J. S. Harwood, L. Frydman (1995) J. Am. Chem. Soc. 117, 12779

MQMAS IN $(CO)_5$ Mn-PbPh$_3$ at 21.1 T



After shearing transformation:

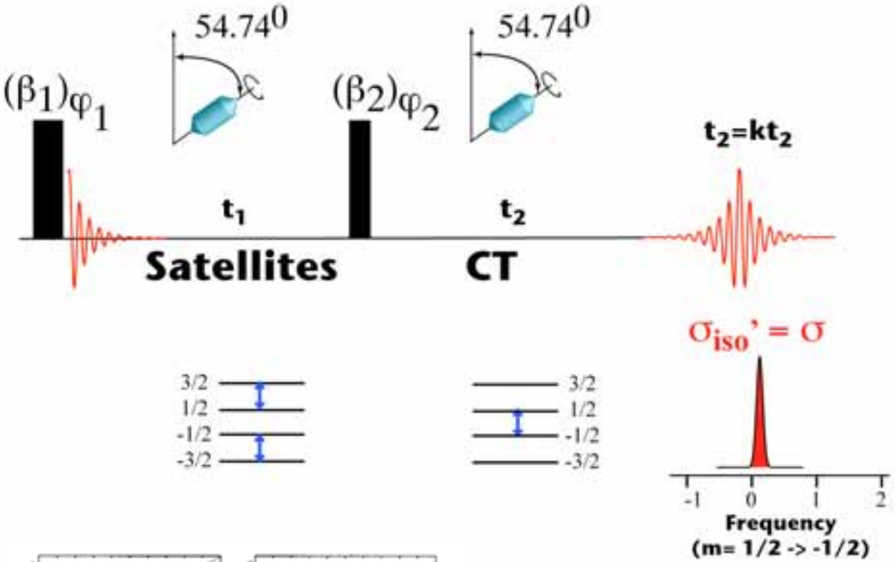


K. J. Ooms, K. W. Feindel, V. V. Terskikh, R. Wasylishen, Inorg. Chem. 2006, 45, 8492-8499 (cover article; figure courtesy of Kris Ooms)

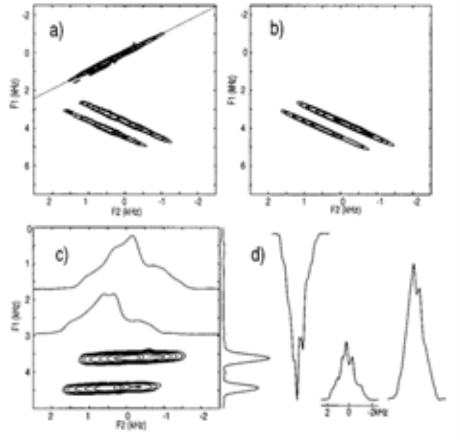
SPATIAL AVERAGING: STMAS EXPERIMENT

Refocusing of anisotropic frequencies with STMAS echo

The satellite transition MAS spectrum is the mirror image of central transition MAS spectrum



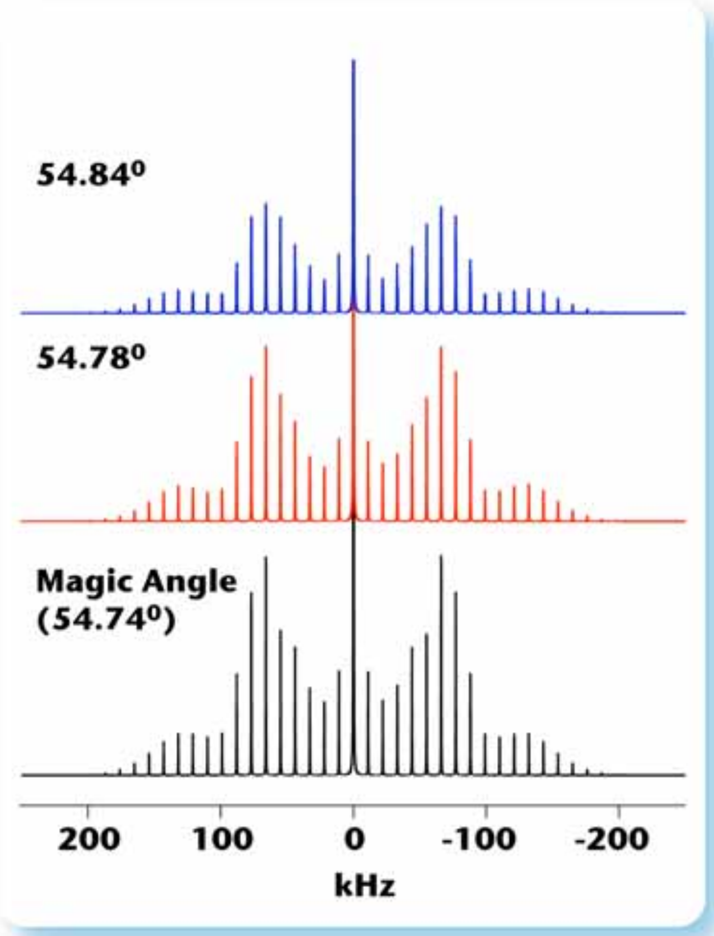
Spin	Transition	K
3/2	1st satellites	8/9
5/2	1st satellites	7/24
	2nd satellites	11/6
7/2	1st satellites	28/45
	2nd satellites	23/45
	3rd satellites	12/5
9/2	1st satellites	55/72
	2nd satellites	1/18
	3rd satellites	9/8
	4th satellites	25/9



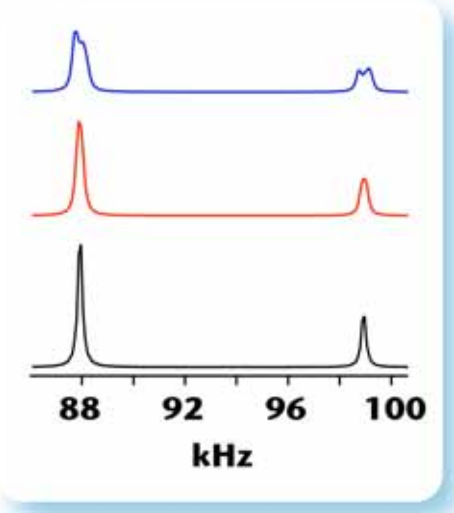
^{23}Na STMAS spectra of $Na_2SO_4/Na_2C_2O_4$ mixture

Z. Gan (2000) J. Am. Chem. Soc. 122, 3242-3243

ADDITIONAL PRACTICAL CONSIDERATIONS: MAGIC ANGLE SETUP



^{23}Na MAS of $NaNO_3$
C_Q = 337 kHz



Practical guide to SSNMR of half-integer quadrupoles: A. P. M. Kentgens (1997) Geoderma 80, 271-306

ADDITIONAL PRACTICAL CONSIDERATIONS: SELECTIVE VS. NON-SELECTIVE PULSES

NON-SELECTIVE EXCITATION: $\omega_{RF} >> \omega_Q$

pulse response for the central transition: sinusoidal modulation of signal intensity as a function of the pulse length τ, with frequency ω_{RF}:

$$S(\tau) = [3(I+1/2)/4I(I+1)] \cdot \sin(\omega_{RF}\,\tau)$$

SELECTIVE EXCITATION: $\omega_{RF} << \omega_Q$

pulse response for the central transition:

$$S(\tau) = [3/4I(I+1)] \cdot \sin((I+1/2)\omega_{RF}\,\tau)$$

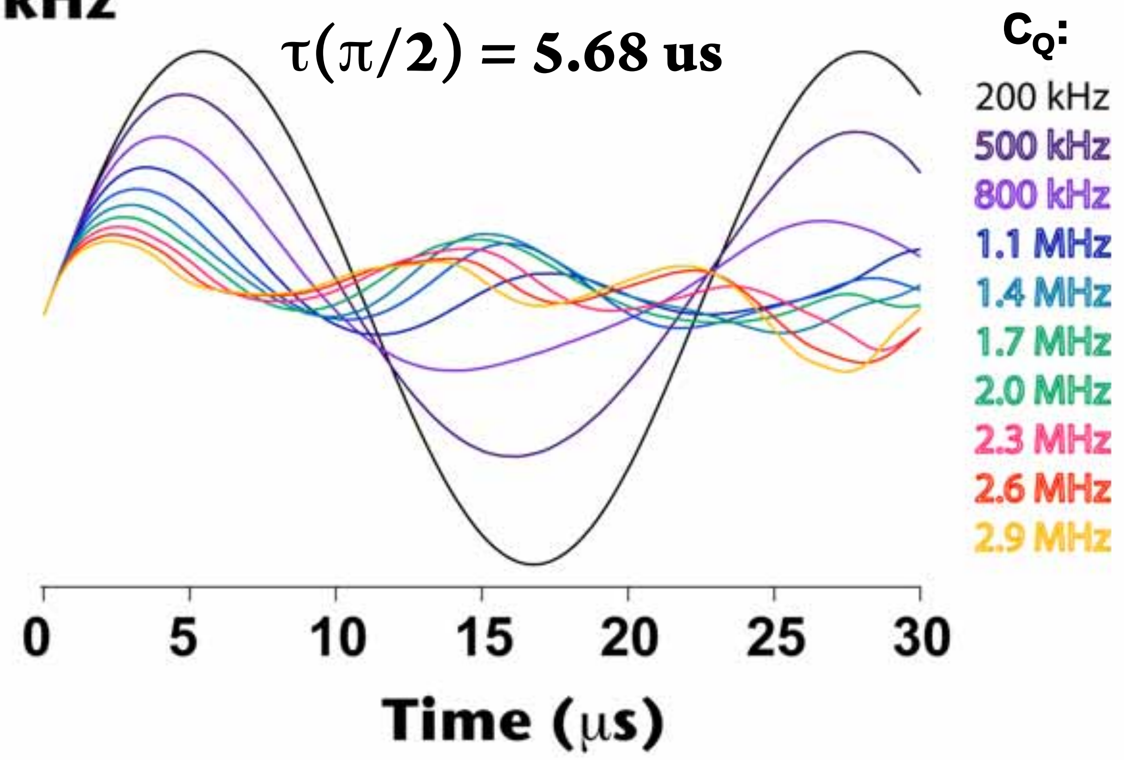
INTERMEDIATE REGIME: $\omega_{RF} \sim \omega_Q$

complex pulse response for the central transition; basis for nutation spectroscopy and numerical calculations to determine C_Q

Practical guide to SSNMR of half-integer quadrupoles: A. P. M. Kentgens (1997) Geoderma 80, 271-306

ADDITIONAL PRACTICAL CONSIDERATIONS: NUTATION SPECTROSCOPY

Spin-7/2
ω_{RF} = 44 kHz
no CSA



$\tau(\pi/2) = 5.68$ us

Curves simulated in SIMPSON;
Original reference: A. Samoson, E. Lipmaa, J. Magn. Reson. (1988) 79, 255-268

RELATING NMR OBSERVABLES TO MOLECULAR STRUCTURE

NMR Spectrum ←→ NMR Parameters ←→ Local geometry

↕

Chemical structure (reactivity)

I. Determination of experimental NMR parameters from numerical simulations

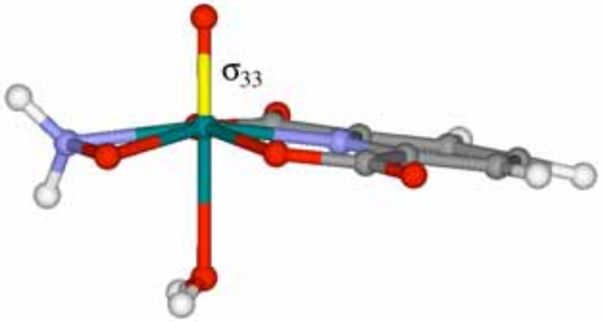
Find unique solution to C_Q, η_Q, δ_σ, η_σ, α, β, γ

II. Theoretical prediction of NMR parameters from model molecular geometry

Classical electrostatic model (EFG)- only in simple ionic compounds
Quantum mechanical calculations (Density Functional Theory) (EFG, CSA)

DFT CALCULATIONS CAN EXPLAIN THE MAGNITUDE OF C_Q

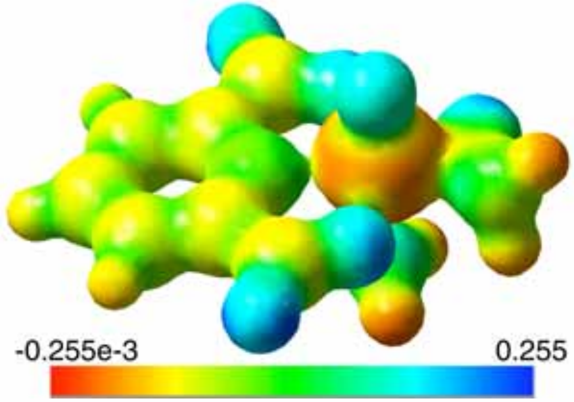
^{51}V SPECTROSCOPY OF DIPICOLINIC ACID DERIVATIVES



Nominal coordination geometry: heptacoordinate, large C_Q expected

Experimental C_Q: 3.43 MHz (small)

Electrostatic potential surface (ESP):



Reveals capped square planar charge distribution, consistent with small C_Q

Ooms, Bolte, Baruah, Smee, Crans, Polenova (2007) Inorg. Chem. 46, 9285-9293

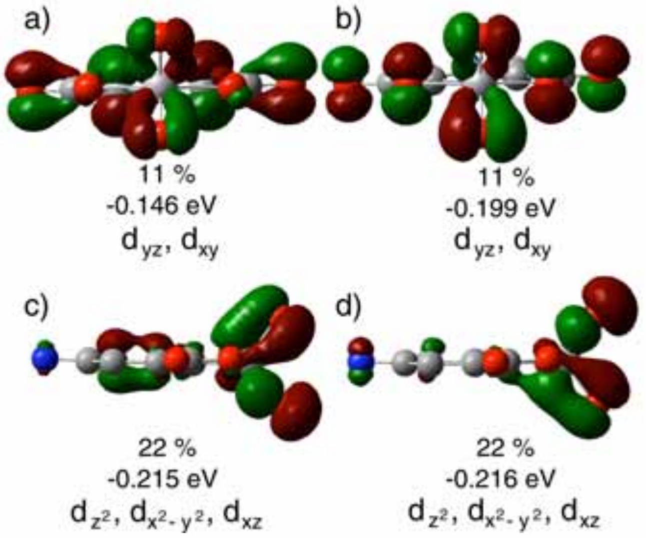
DFT ANALYSIS OF MOLECULAR ORBITALS

^{51}V SPECTROSCOPY OF DIPICOLINIC ACID DERIVATIVES

EXAMINE THE SYMMETRY OF MO'S TO

UNDERSTAND THE CONTRIBUTIONS TO

THE ^{51}V MAGNETIC SHIELDING TENSOR



a) 11 % -0.146 eV d_{yz}, d_{xy}

b) 11 % -0.199 eV d_{yz}, d_{xy}

c) 22 % -0.215 eV d_{z^2}, $d_{x^2-y^2}$, d_{xz}

d) 22 % -0.216 eV d_{z^2}, $d_{x^2-y^2}$, d_{xz}

Bolte, Ooms, Baruah, Smee, Crans, Polenova (2008) J.Chem. Phys.

METALS NMR IN BIOLOGICAL SOLIDS:

SELECTED EXAMPLES

INFORMATION CONTENT OF HALF-INTEGER QUADRUPOLES SSNMR

Presence of a particular metal site (sometimes indiscernible in X-ray structures)

Geometry of metal sites

Electronic structure of metal sites (i.e., interactions with surrounding ligands and/or solvent molecules)

Protonation states of ligands

Identification of polymorphs

Dynamics of metals and/or coordinated ligands

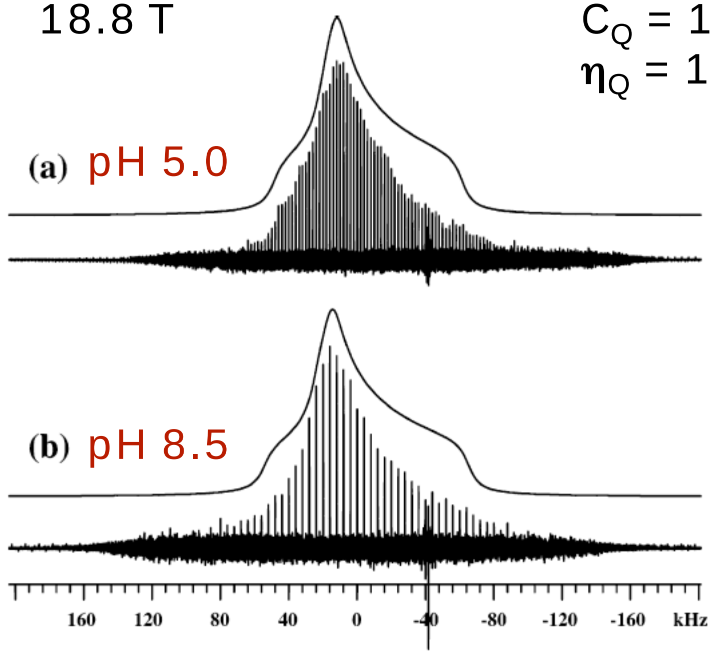
This information- sheds light on chemical reactivity of metal sites in metallobiomolecules, often unavailable from other techniques

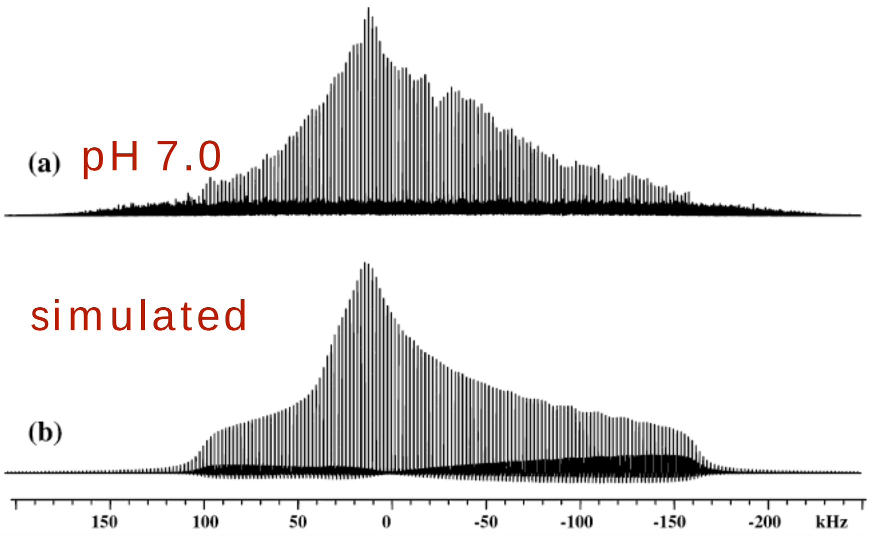
EXAMPLE 1:
^{67}Zn SSNMR OF CARBONIC ANHYDRASE

18.8 T

C_Q = 10.5 MHz
η_Q = 1.0

9.4 T



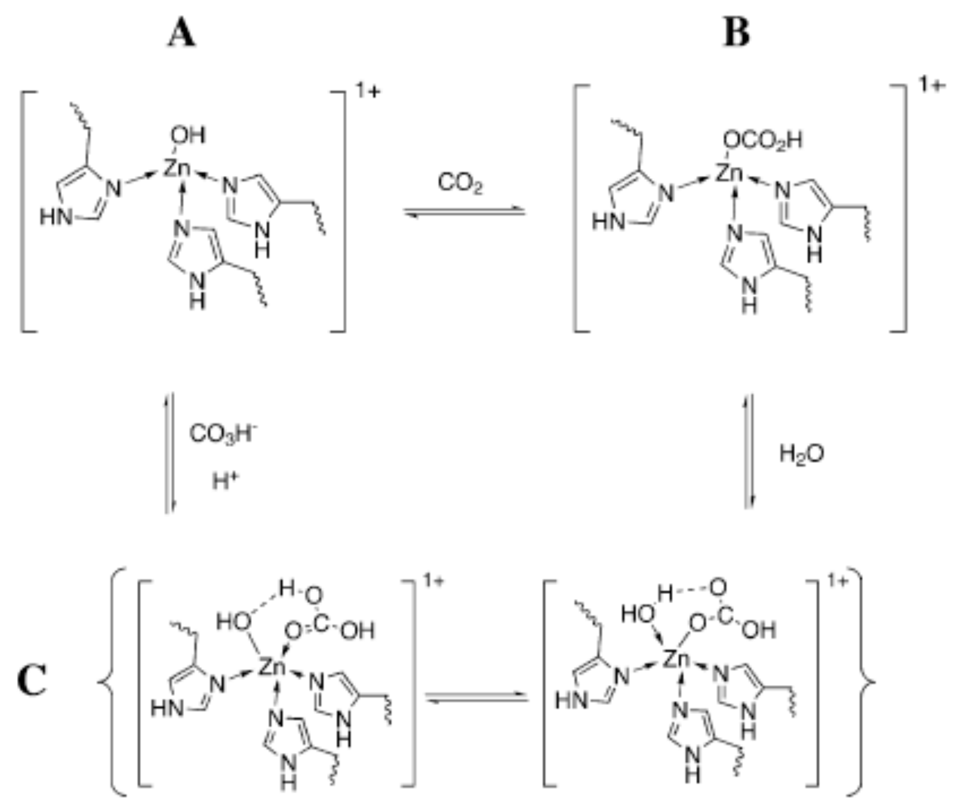


Spectra are pH-independent contrary to the proposed catalytic mechanism; DFT calculations indicate hydroxide coordinated to Zn (C_Q = 8-10 MHz) and rule out water ligand (C_Q = 25-35 MHz, inconsistent with the SSNMR results)

A. S. Lipton, R. W. Heck, P. D. Ellis (2004) J. Am. Chem. Soc. 126, 4735-4739

EXAMPLE 1:
^{67}Zn SSNMR OF CARBONIC ANHYDRASE

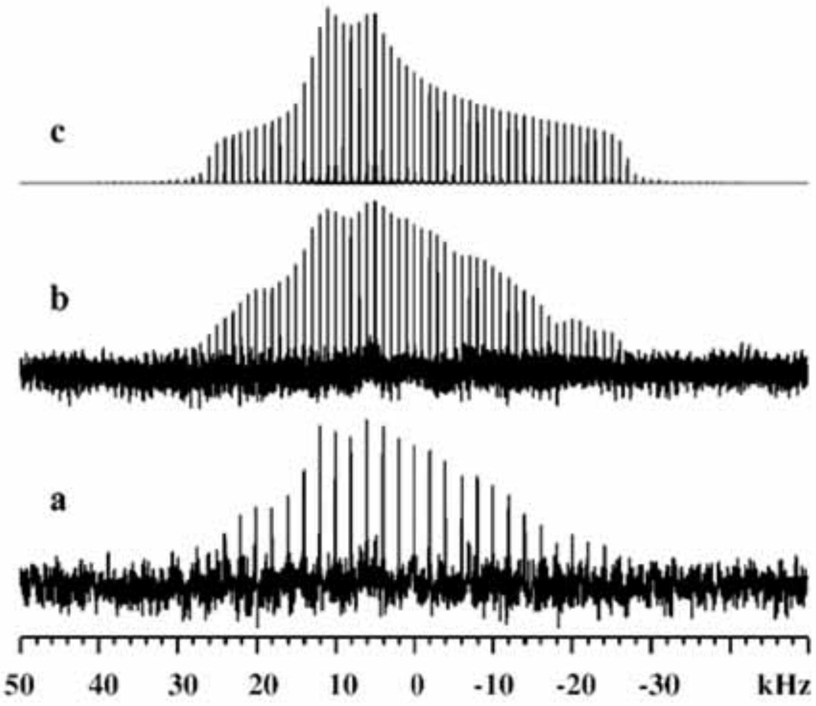
Revised mechanism proposed from ^{67}Zn SSNMR results;
accounts for the pH-independent spectra and coordinated hydroxide



A. S. Lipton, R. W. Heck, P. D. Ellis (2004) J. Am. Chem. Soc. 126, 4735-4739

EXAMPLE 2: ^{67}Zn SSNMR OF HUMAN NUCLEOTIDE EXCISION REPAIR PROTEIN XPA

C_Q = 4.9 MHz
η_Q = 0.84
δ_{iso} = 327.6 ppm

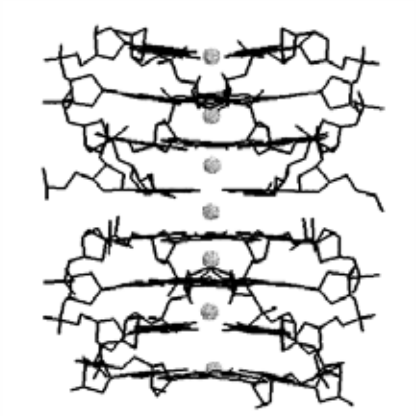


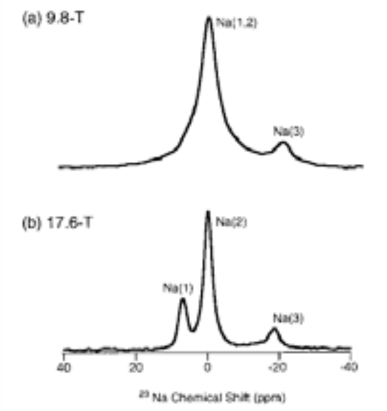
(a) Experimental ^{67}Zn NMR spectrum of XPA-MBD at 9.4 T and 25 K, with 25 Hz conventional line boadening (LB), (b) Data from part apodized with 5 Hz conventional and 1 kHz matched LB and zero filled to double the echo spacing, and (c) simulation utilizing parameters described in the text with 25 Hz conventional and 1.5 kHz matched LB. All spectra are conventionally zero filled to 512 kpoints.

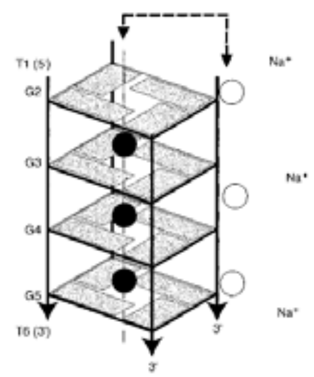
A. S. Lipton, G. W. Buchko, J. A. Sears, M. A. Kennedy, P. D. Ellis (2001) J. Am. Chem. Soc. 123, 992-993

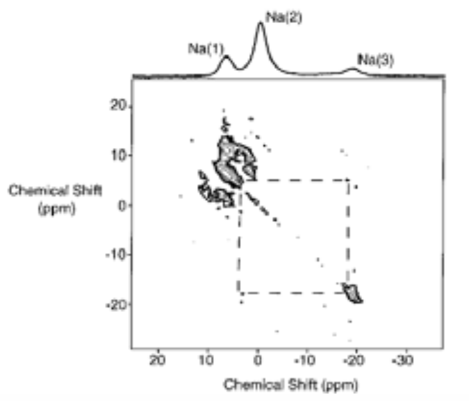
EXAMPLE 4:
^{23}Na SSNMR OF Na^{+} IN A DNA QUADRUPLEX

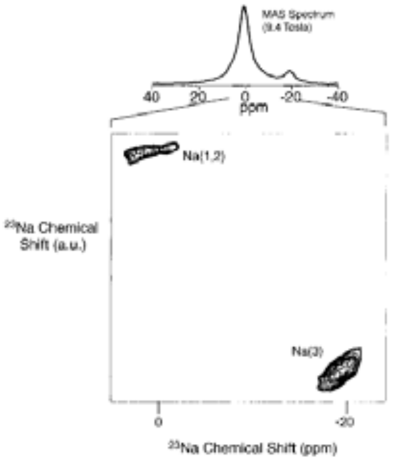
^{23}Na SSNMR spectra reveal three types of sodium and the presence of motions in the quadruplex; Intriguing hypothesis that motions are axial rotations of the stacked G-quartet assembly

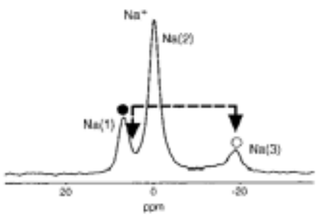








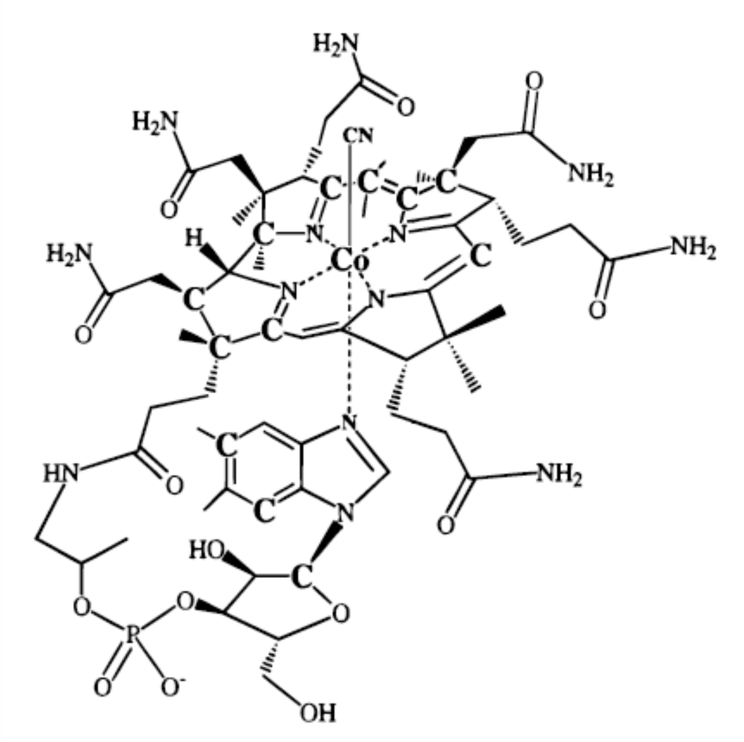


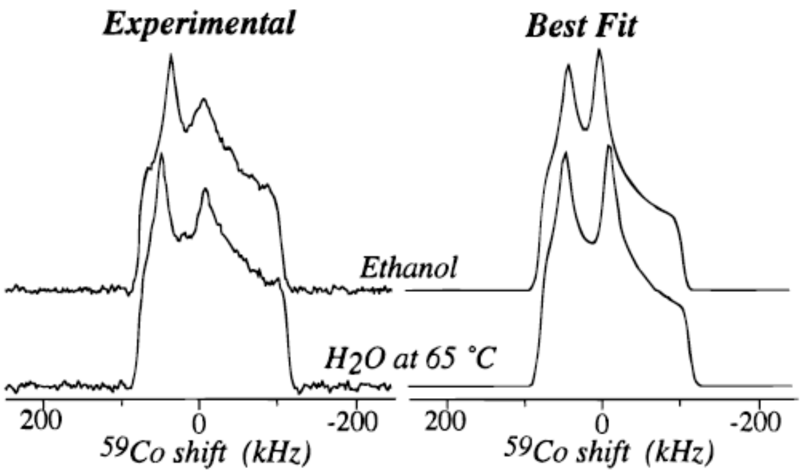


D. Rovnyak, M. Baldus, G. Wu, N. V. Hud, J. Feigon, R. G. Griffin (2000) J. Am. Chem. Soc. 122, 11423-11429

EXAMPLE 5:
^{59}Co SSNMR OF VITAMIN B_{12} POLYMORPHS

^{59}Co SSNMR spectra reveal presence of two polymorphs of vitamin B_{12}





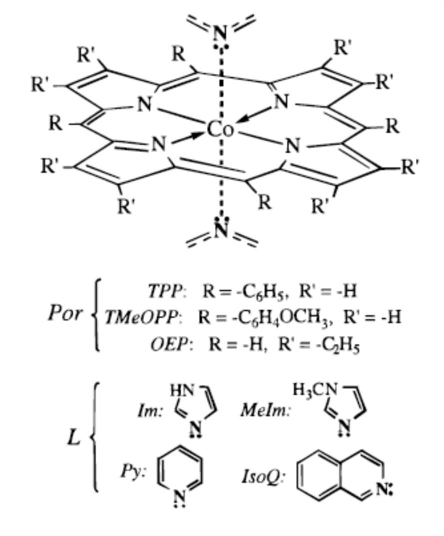
"Wet": $C_Q = 27.8 \pm 0.3$ MHz

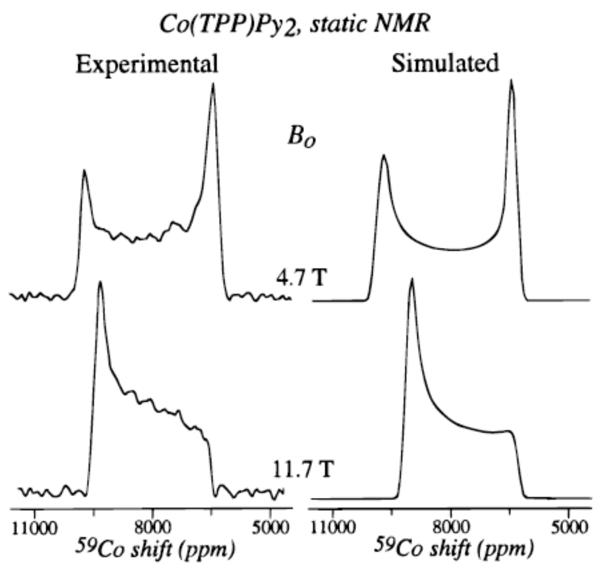
"Dry": $C_Q = 26.1 \pm 0.4$ MHz

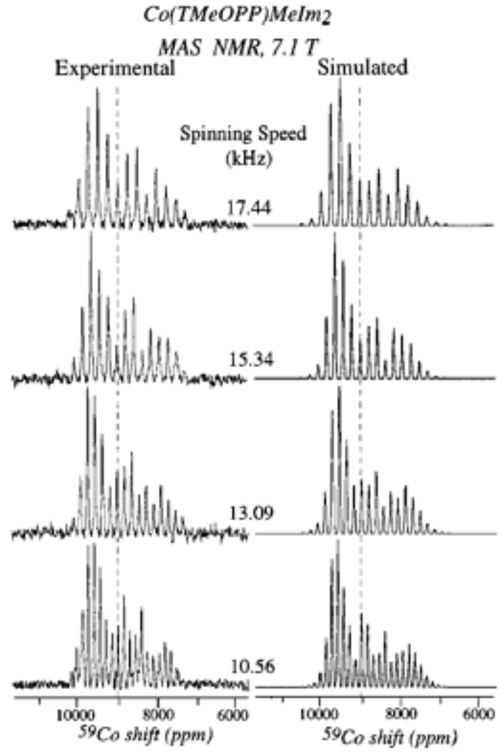
A. Medek and L. Frydman (2000) J. Am. Chem. Soc. 122, 684-691

EXAMPLE 6:
^{59}Co SSNMR OF PORPHYRIN COMPLEXES

^{59}Co SSNMR spectra exhibit large shielding and quadrupolar anisotropies; experimental anisotropies deviate for those expected for octahedal complexes; interaction is proposed between the metal orbitals and the aromatic ligand orbitals

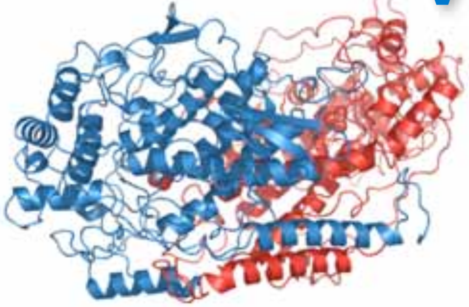




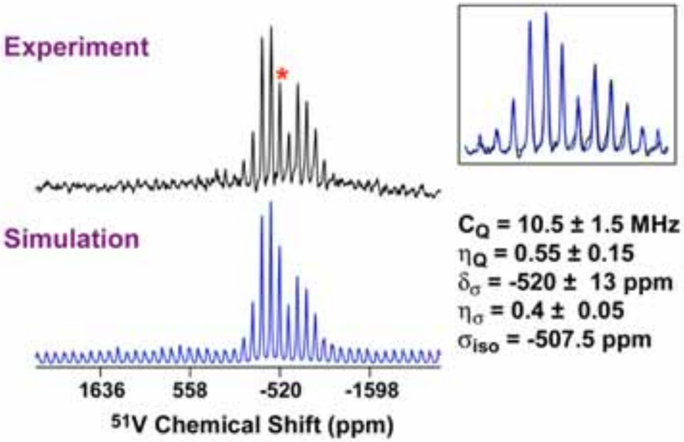


A. Medek, V. Frydman, and L. Frydman (1997) J. Phys. Chem. 101, 8959-8966

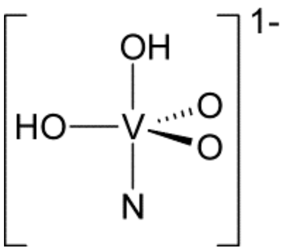
EXAMPLE 8:
^{51}V SSNMR OF VANADIUM HALOPEROXIDASES

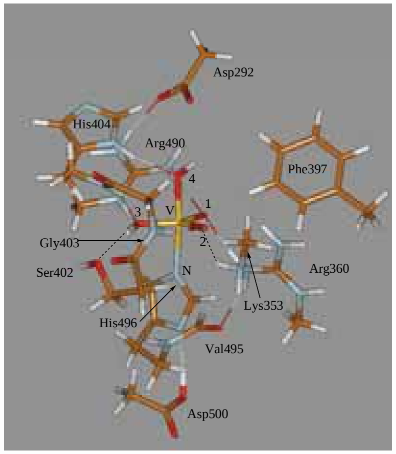


^{51}V SSNMR spectra of vanadium chloroperoxidase- reveal unexpected protonation states of the vanadate cofactor



C_Q = 10.5 ± 1.5 MHz
η_Q = 0.55 ± 0.15
δ_σ = -520 ± 13 ppm
η_σ = 0.4 ± 0.05
σ_{iso} = -507.5 ppm





Experiment

DFT calculations

Pooransingh-Margolis, Renirie, Hasan, Wever, Vega, Polenova (2006) J. Am. Chem. Soc., 128 (15), 5190-5208

SOME BOOKS AND GENERAL REVIEWS ON QUADRUPOLES

M. H. Cohen and F. Reif “Quadrupole Effects in Nuclear Magnetic Resonance Studies in Solids” Solid St. Phys. 5: 321-438 (1957)

A. Abragam “Principles of Nuclear Magnetism” (1963) Oxford University Press, Oxford

E. W. Wooten, K. T. Mueller, A. Pines “New Angles in Nuclear-Magnetic-Resonance Sample Spinning” (1992) Acct. Chem. Res. 25, 209-215

D. Freude and J. Haase “Quadrupole Effects in Solid-State Nuclear Magnetic Resonance” (1993) In: “NMR. Basic Principles and Progress” Vol. 29, Springer, Berlin, pp. 1-90

L. B. Alemany “Critical Factors in Obtaining Meaningful Fast MAS NMR Spectra of Non-Integral Quadrupolar Nuclei. A Review with Particular Emphasis on 27Al MAS NMR of Catalysts and Minerals” (1993) Appl. Magn. Reson., 4, 179

P. J. Grandinetti “Dynamic-Angle Spinning and Applications” (1995) in Encyclopedia of Nuclear Magnetic Resonance, John Wiltey and Sons

A. P. M. Kentgens “A Practical Guide to Solid-State NMR of Half-Integer Quadrupolar Nuclei with Some Applications to Disordered Systems” (1997) Geoderma 80, 271-306 (and references therein)

M. E. Smith ME and E. R. H. van Eck “Recent advances in experimental solid state NMR methodology for half-integer spin quadrupolar nuclei” (1999) Prog. NMR Spectr. 34 (2): 159-20

L. Frydman “Spin-1/2 and beyond: A perspective in solid state NMR spectroscopy (2001) Annu. Rev. Phys. Chem. 52: 463-498 2001

M. J. Duer “Solid-State NMR Spectroscopy: Principles and Applications” (2002) Blackwell Science

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