

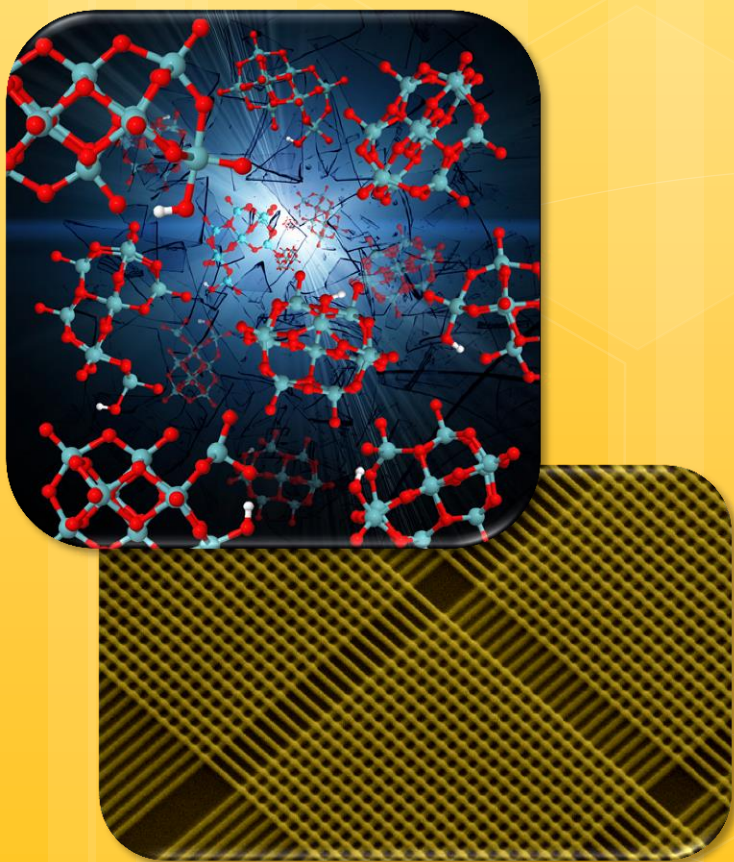
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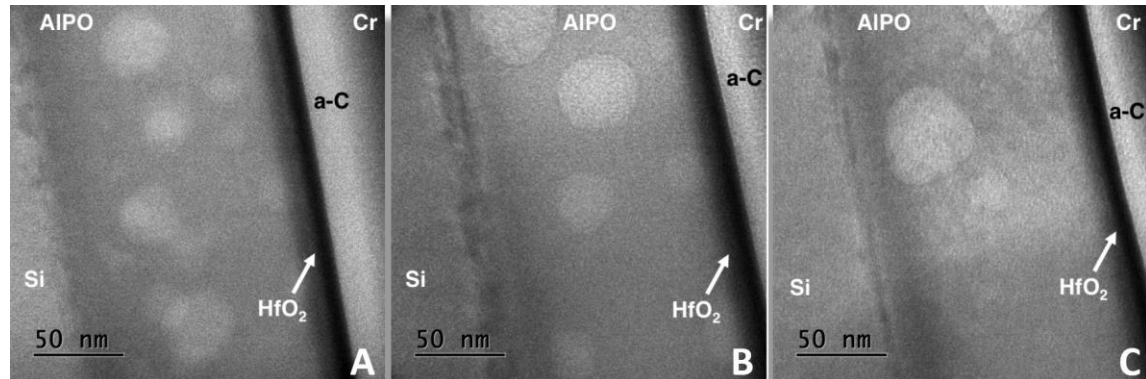
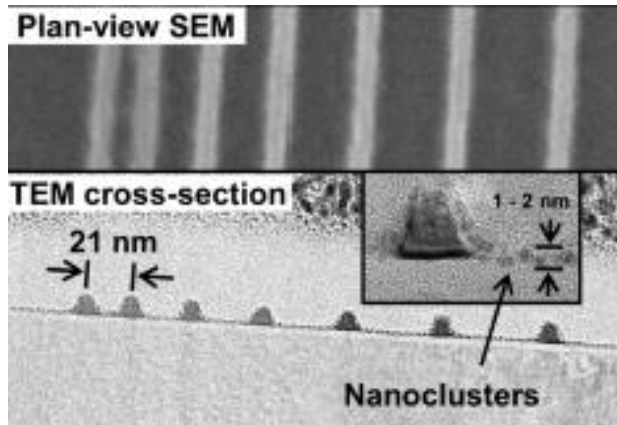
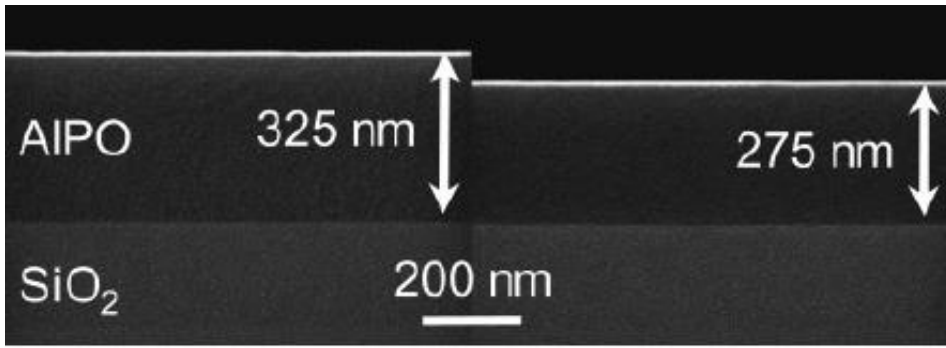
# NMR of Half-Integer Quadrupolar Nuclei in Materials: Opportunities at Ultrahigh Fields

Sophia Hayes

Washington University in St. Louis



# Modern Materials Science Needs New Tools for Structure Determination



# Real Materials – Apple Displays

iMac  
with Retina 5K display

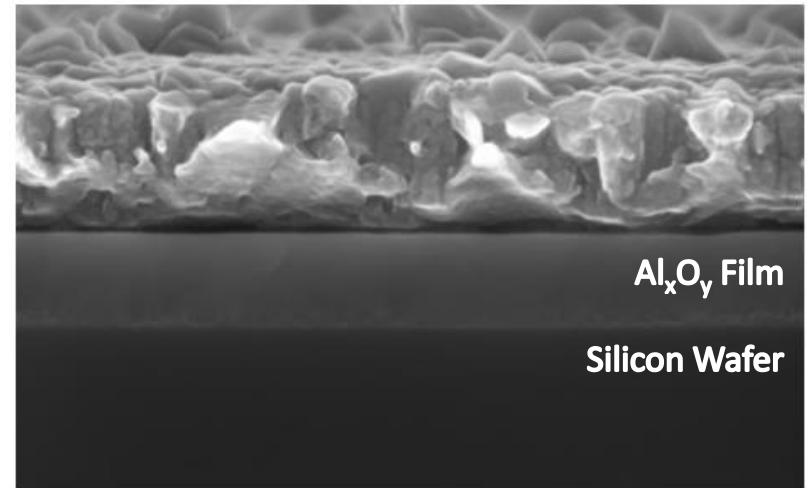
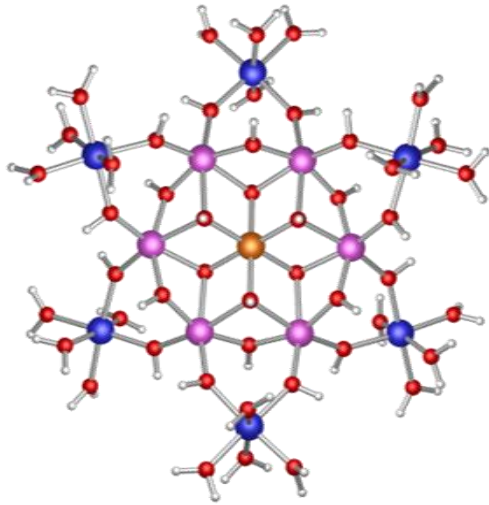


## Oxide TFT

“..we took cues from the groundbreaking oxide thin film transistor ...”

## Patent

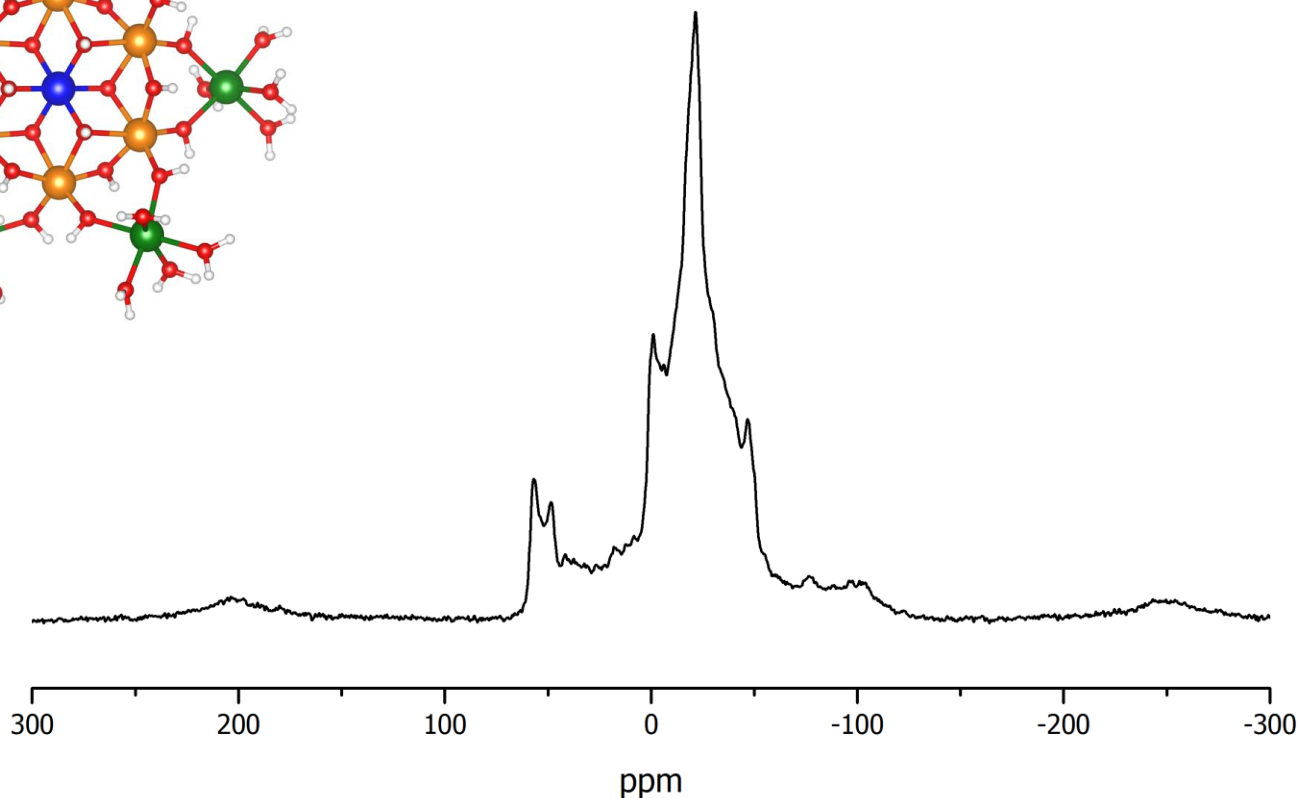
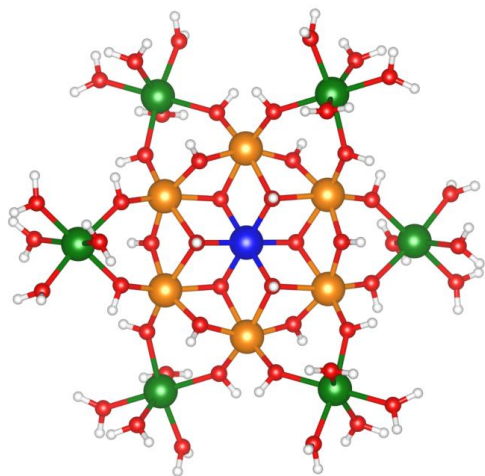
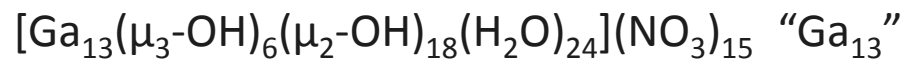
“Embodiments described herein may provide an oxide thin-film transistor (TFT) ... the semiconductor layer may include or incorporate other materials, for example, zinc oxide (**ZnO**), indium oxide (**InO**), gallium oxide (**GaO**), tin oxide (**SnO<sub>2</sub>**), indium gallium oxide (**IGO**), indium zinc oxide (**IZO**), zinc tin oxide (**ZTO**), and indium zinc tin oxide (**IZTO**) among others.”



# A TALE OF TWO MATERIALS: A CASE STUDY IN QUADRUPOLEAR NMR

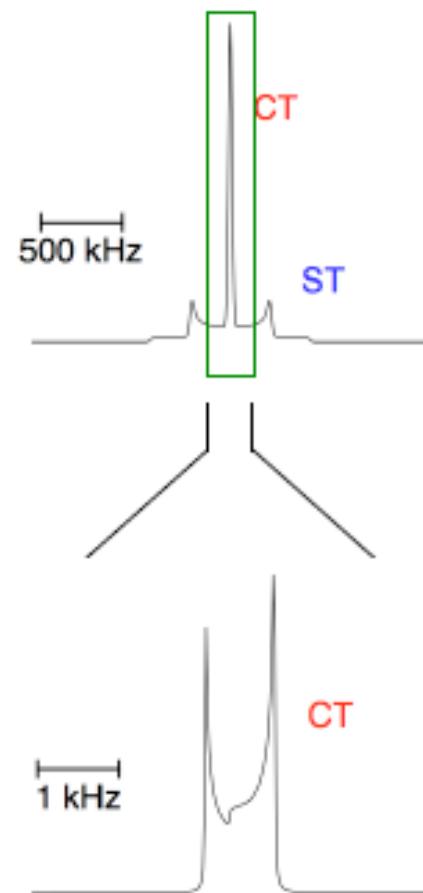
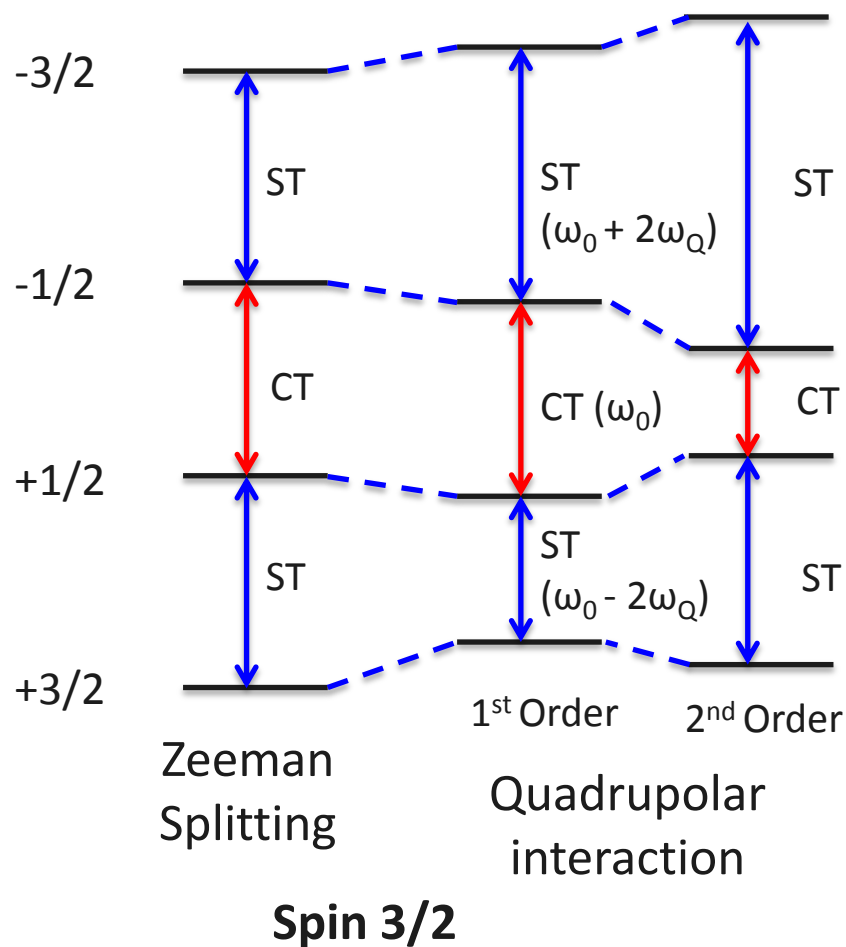
**(REAL MATERIALS)**

# Solid-state NMR



(<sup>71</sup>Ga MAS, 21T Ga<sub>13</sub>)

# Quadrupolar Nuclei



# Quadrupolar Nuclei

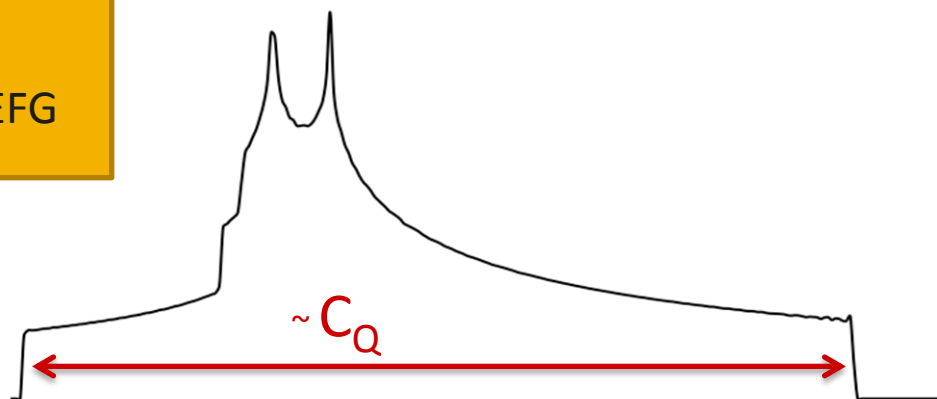
*central transition lineshapes under MAS*

## **Quadrupole Coupling Constant:**

$eQ$  = nuclear quadrupolar moment

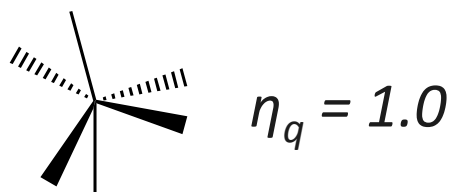
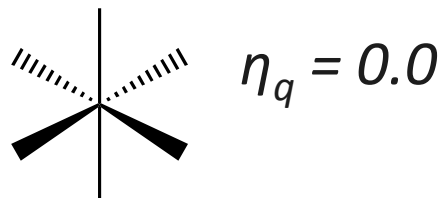
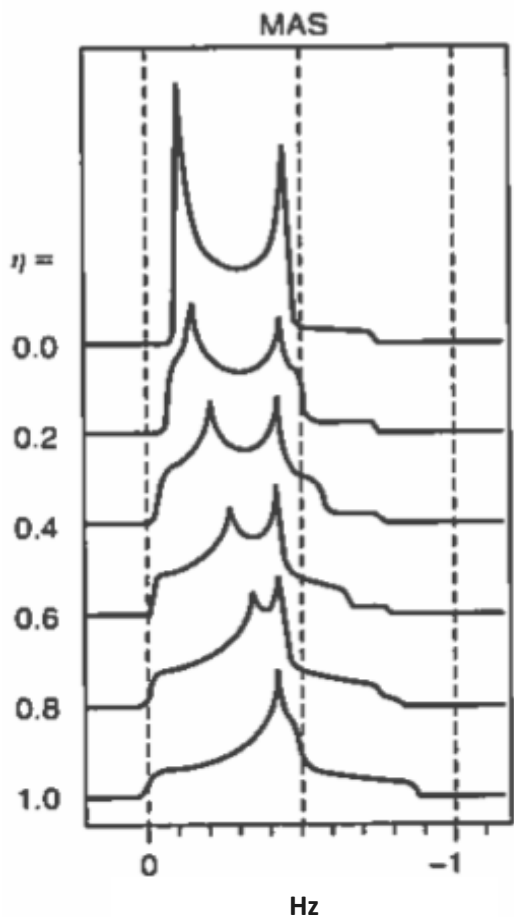
$V_{zz}$  = largest principle component of EFG

$$C_Q = \frac{(e^2 q Q)}{h} = \frac{eQ(V_{zz})}{h}$$



# Quadrupolar Nuclei

*central transition lineshapes under MAS*



**Quadrupole Parameter:**

$$\eta_q = (V_{xx} - V_{yy}) / V_{zz} \quad 0 < \eta_q < 1$$

$$|V_{zz}| \geq |V_{yy}| \geq |V_{xx}|$$

$$V_{xx} + V_{yy} + V_{zz} = 0$$



# Why is field dependence important?

## Second-order quadrupolar broadening

- Second-order quadrupolar frequency for an energy level/transition can be described (for  $\eta_Q = 0$ ) by

$$\omega \propto \frac{(\omega_Q^{\text{PAS}})^2}{\omega_0} [A + B d_{00}^2(\beta) + C d_{00}^4(\beta)]$$

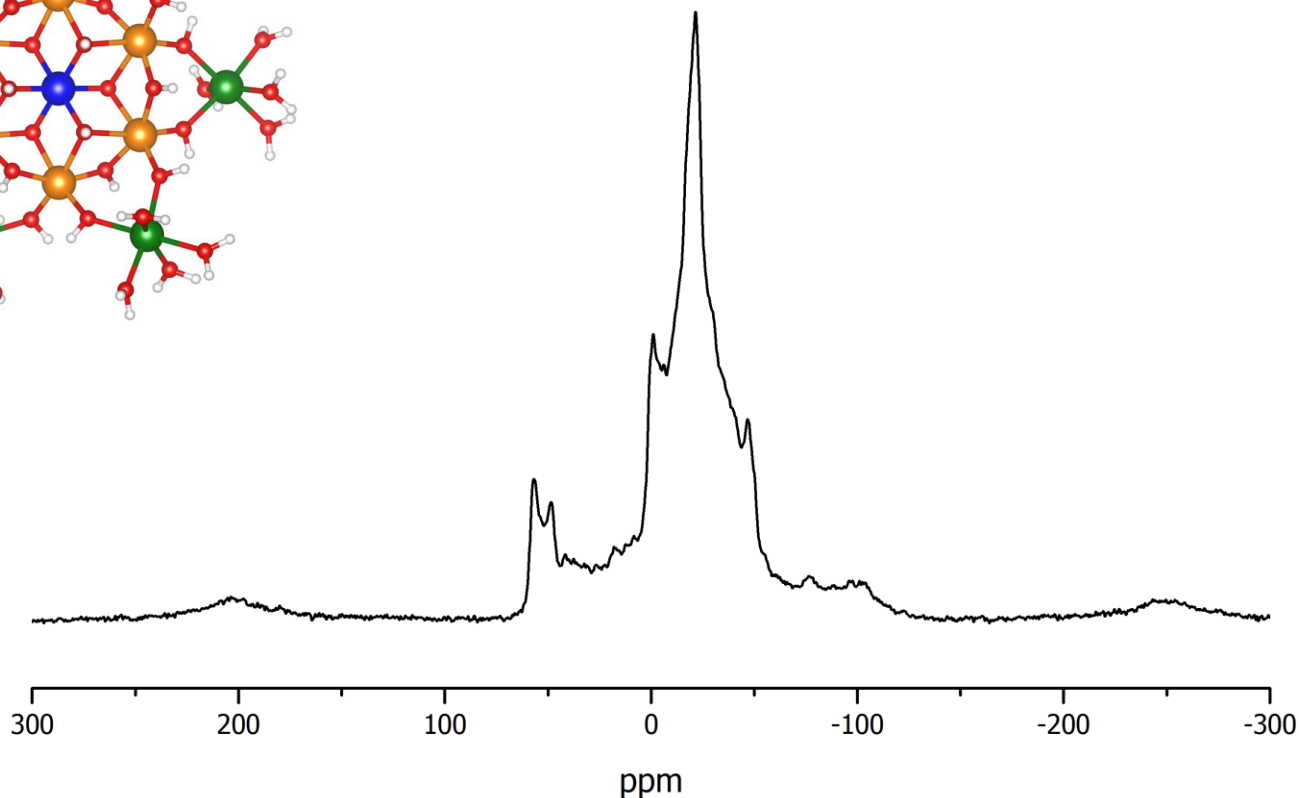
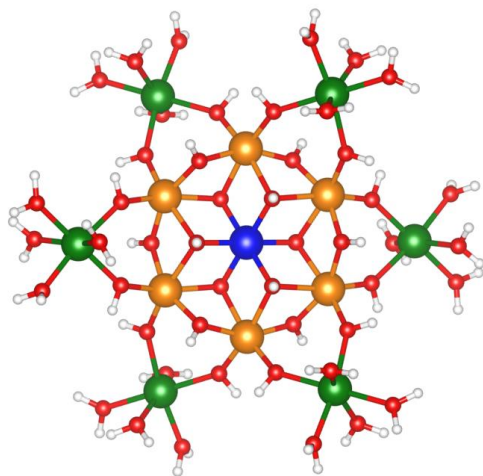
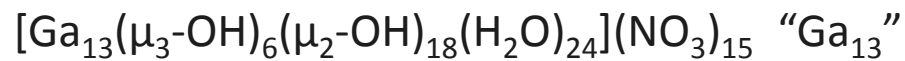
Diagram illustrating the components of the second-order quadrupolar frequency equation:

- Constant depending upon  $C_Q$ ,  $I$  and  $\omega_0$  (indicated by a black arrow pointing to  $A$ )
- Isotropic shift (indicated by a blue arrow pointing to  $B d_{00}^2(\beta)$ )
- Second-rank anisotropic (indicated by a red arrow pointing to  $B d_{00}^2(\beta)$ )
- Fourth-rank anisotropic (indicated by a green arrow pointing to  $C d_{00}^4(\beta)$ )

$$d_{00}^2(\theta) \propto (3 \cos^2 \theta - 1)$$

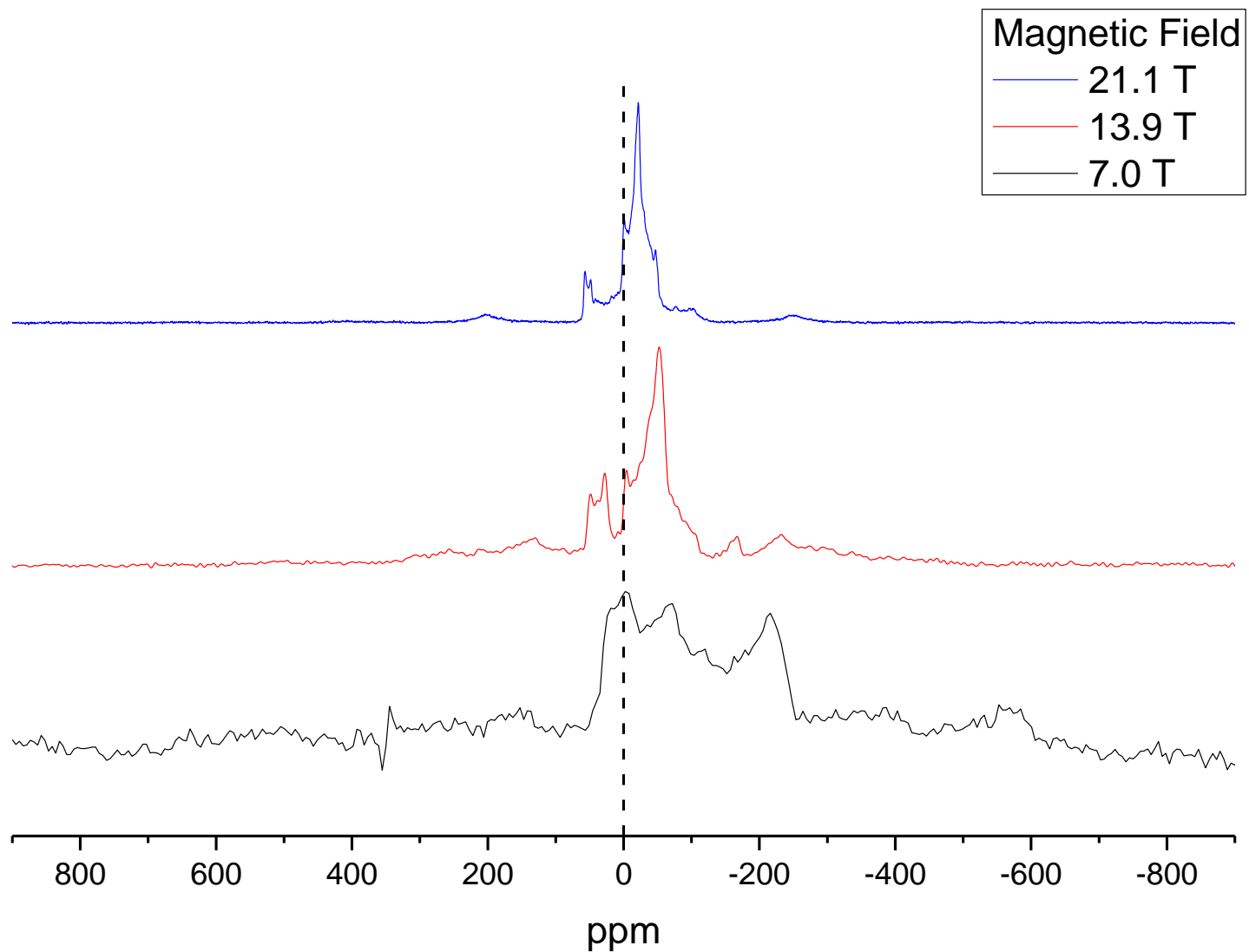
$$d_{00}^4(\theta) \propto (35 \cos^4 \theta - 30 \cos^2 \theta + 3)$$

# Solid-state NMR



(<sup>71</sup>Ga MAS, 21T Ga<sub>13</sub>)

# $^{71}\text{Ga}$ NMR - $\text{Ga}_{13}$ Field Dependence

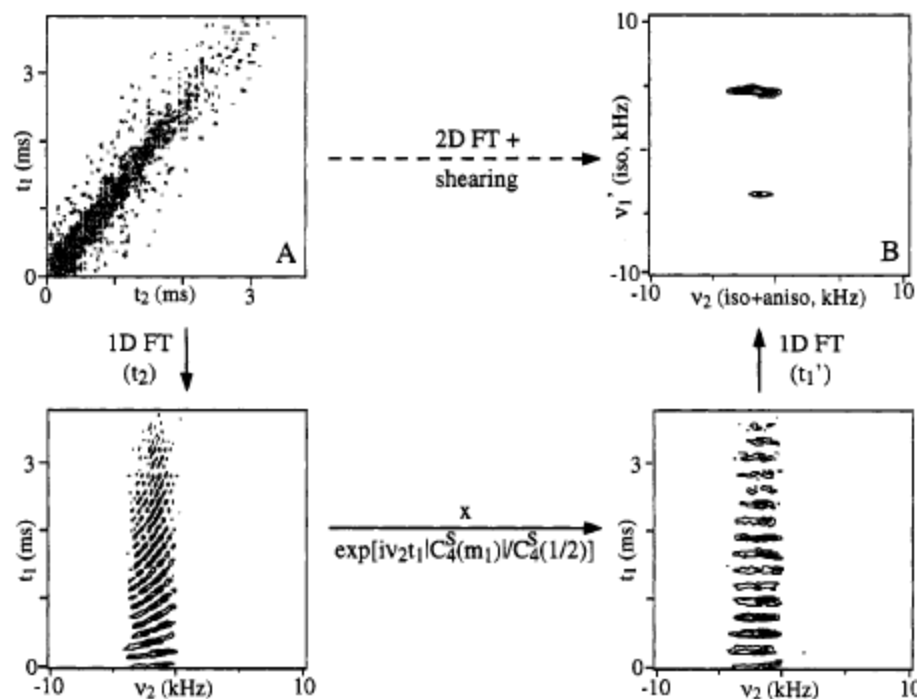


# Multiple-Quantum Magic-Angle Spinning NMR: A New Method for the Study of Quadrupolar Nuclei in Solids

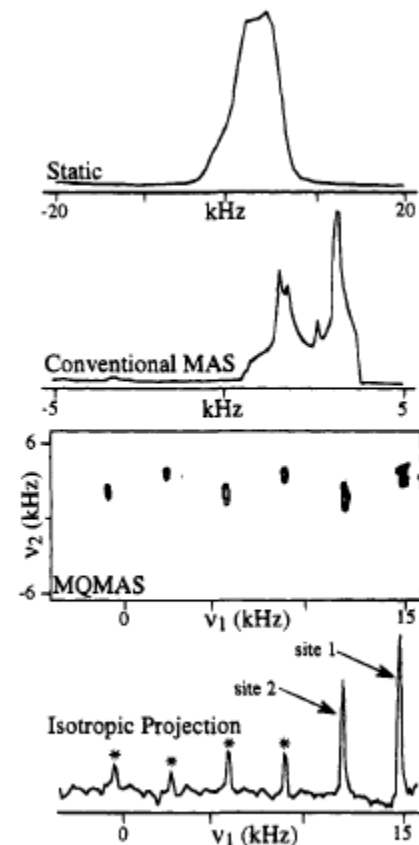
Ales Medek, John S. Harwood, and Lucio Frydman\*

Department of Chemistry (M/C 111), University of Illinois at Chicago, 845 W. Taylor Street, Chicago, Illinois 60607-7061

Received August 24, 1995<sup>Ⓢ</sup>



**Figure 2.** Two-dimensional  $^{23}\text{Na}$  MQMAS NMR of  $\text{Na}_2\text{C}_2\text{O}_4$ . (A) Triple-/single-quantum correlation experiment obtained using the two-pulse sequence shown in Scheme 1. (B) Isotropic/anisotropic correlation spectrum obtained by Fourier transformation and shearing of the time-domain data; the peak at  $\nu_1' \approx 4$  kHz corresponds to the main resonance, the peak at  $\nu_1' = -3$  kHz is a spinning sideband. The shearing was implemented as illustrated in the bottom part of the figure, via a first-order  $t_1$ -dependent phase correction along  $\nu_2$ .



**Figure 10.**  $^{23}\text{Na}$  NMR spectra of polycrystalline  $\text{Na}_2\text{TeO}_3$  acquired under different conditions. The bottom trace corresponds to the projection of the sheared 2D MQMAS spectrum onto the isotropic ( $\nu_1$ ) axis; asterisks correspond to spinning sidebands.



## Acquisition of ultra-wideline NMR spectra from quadrupolar nuclei by frequency stepped WURST-QCPMG

Luke A. O'Dell, Aaron J. Rossini, Robert W. Schurko\*

Department of Chemistry and Biochemistry, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada, N9B 3P4

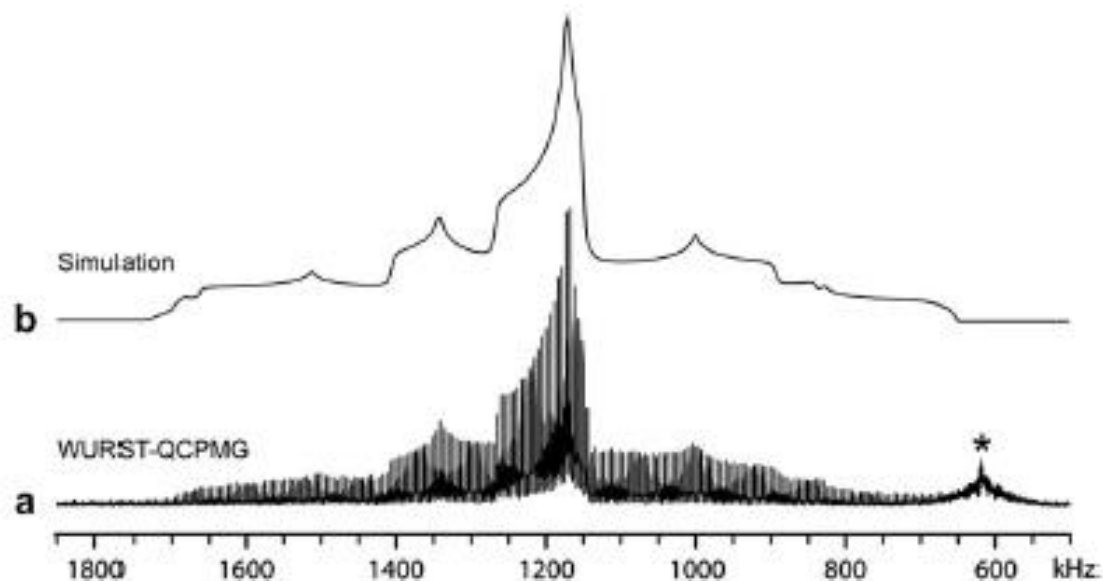


Fig. 4. (a)  $^{29}\text{Co}$  spectrum of  $\text{Co}(\text{acac})_3$  obtained using uncoupled WURST-QCPMG. The full manifold of satellite transition is excited. The asterisk denotes FM radio interference. (b) Simulation made using parameters previously reported [28].



## Acquisition of ultra-wideline NMR spectra from quadrupolar nuclei by frequency stepped WURST-QCPMG

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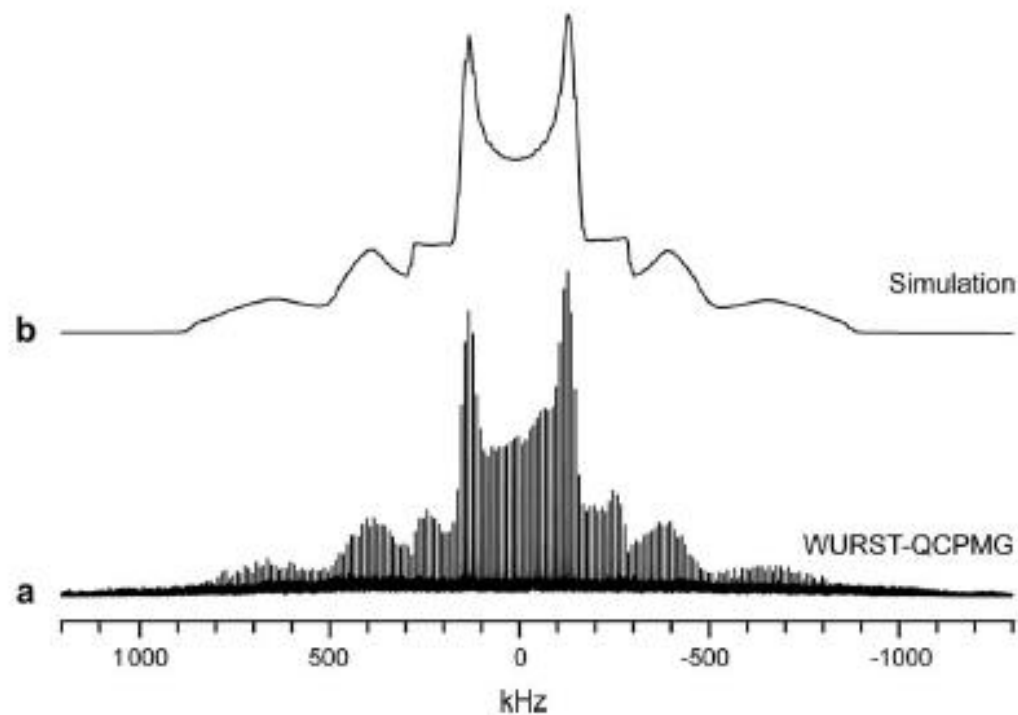
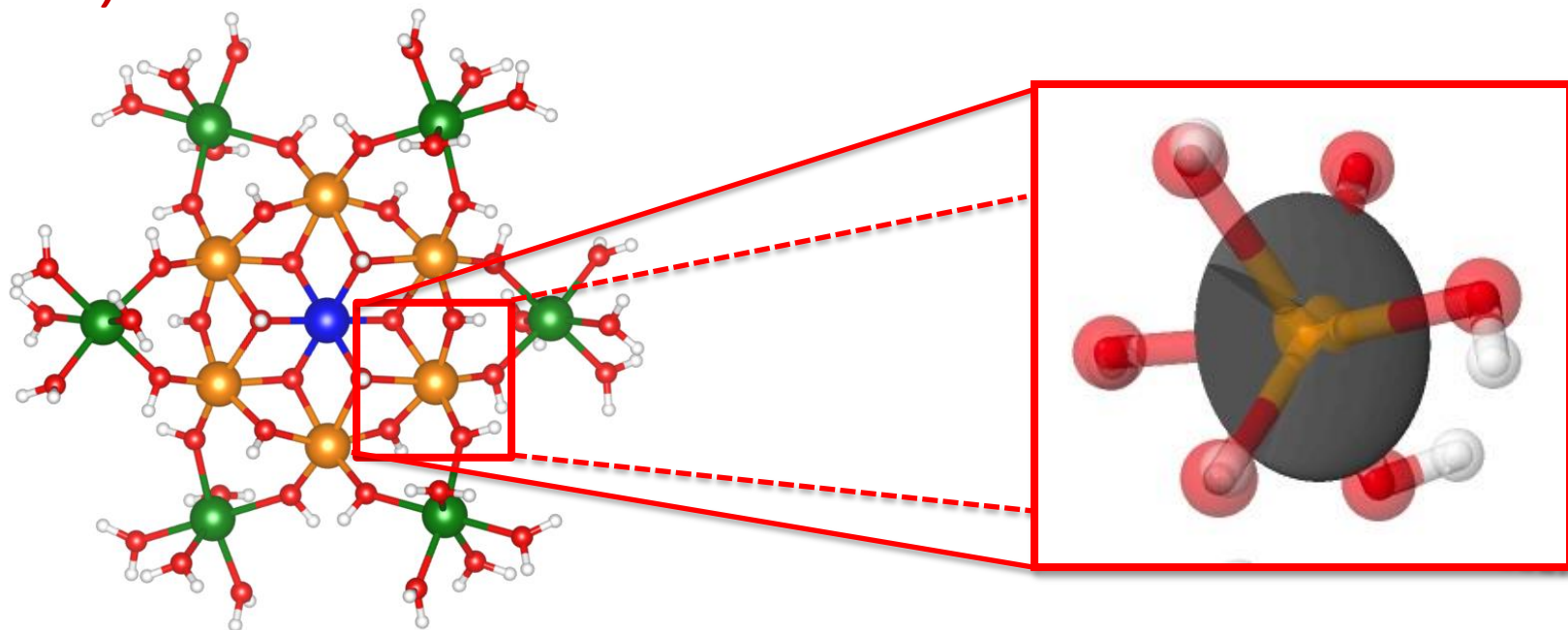


Fig. 5. (a)  $^{10}\text{B}$  natural abundance spectrum of  $\gamma\text{-B}_2\text{O}_3$  obtained in a total experiment time of 0.8 h. (b) Simulation made using parameters previously reported [29].

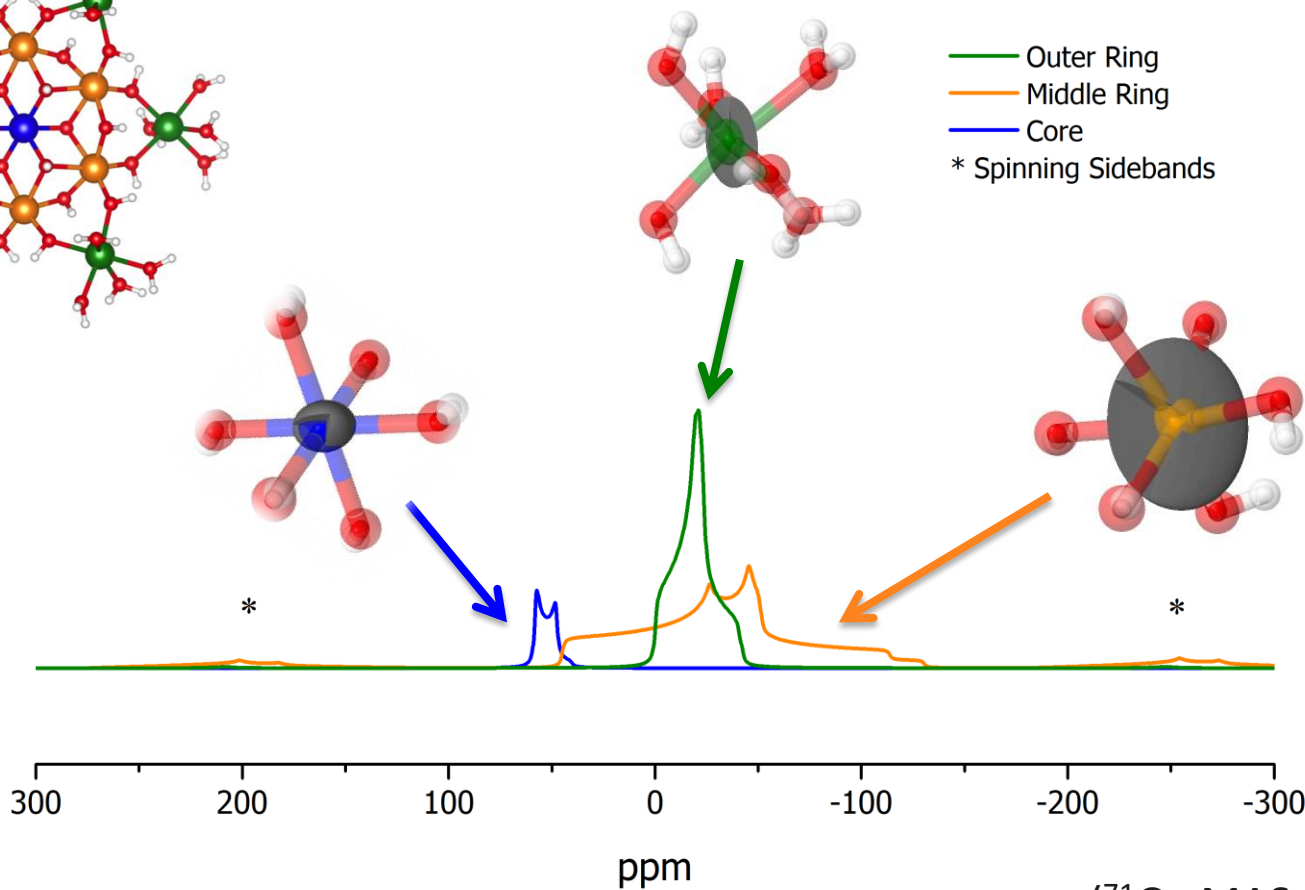
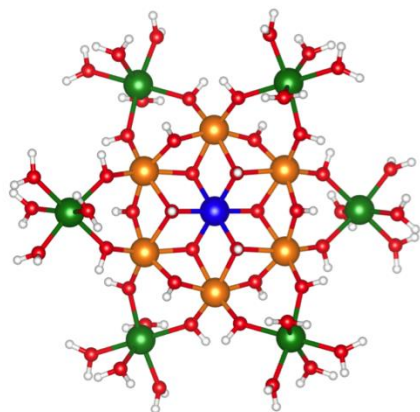
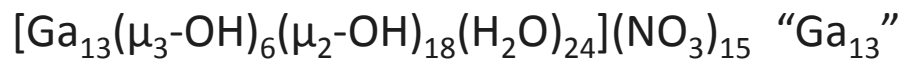
# Can First Principles Calculations Help?

*Electric Field Gradients (CASTEP, Quantum Espresso, VASP)*



- EFG can be calculated based on a 3-D structure (the grey ellipsoid)

# Ga<sub>13</sub> NMR Model

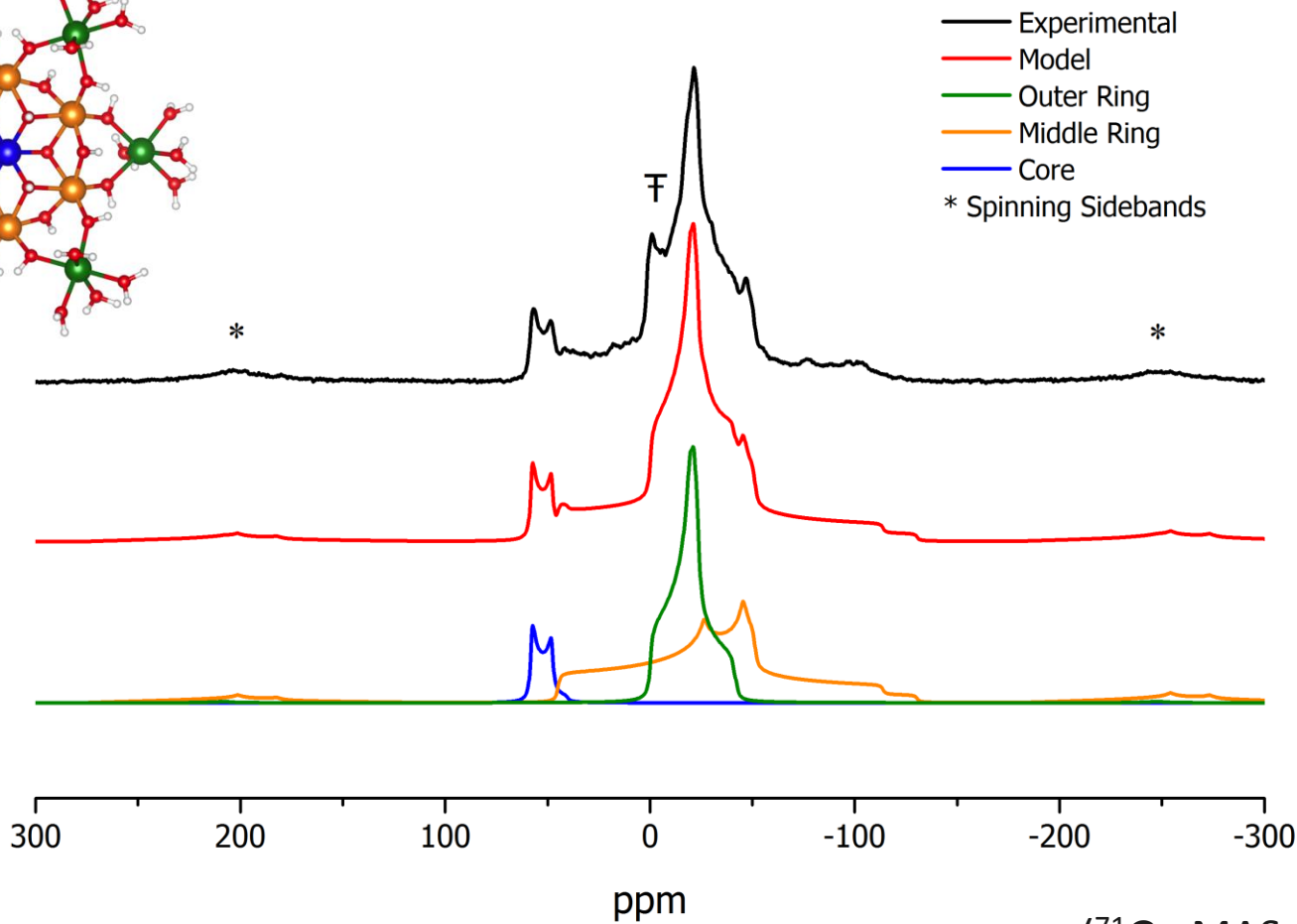
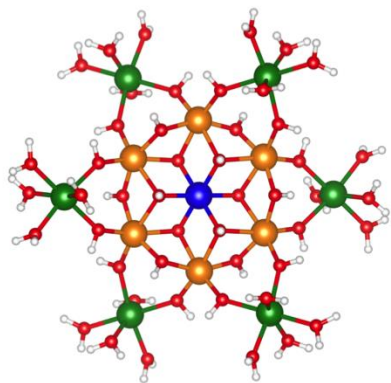
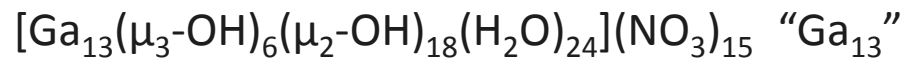


— Outer Ring  
— Middle Ring  
— Core  
\* Spinning Sidebands

(<sup>71</sup>Ga MAS, 21.1T)

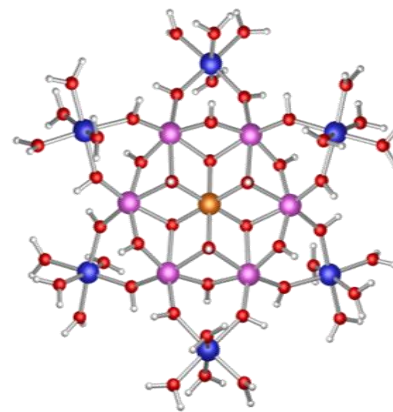


# Ga<sub>13</sub> NMR Model



(<sup>71</sup>Ga MAS, 21.1T)

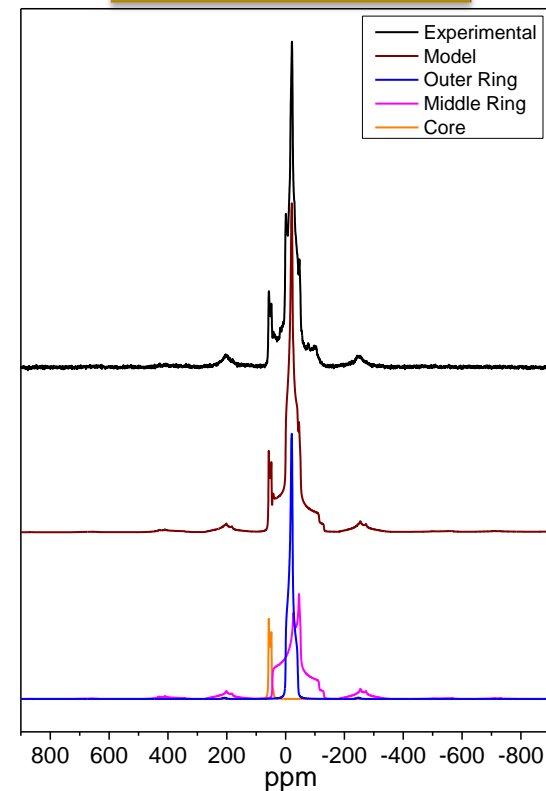
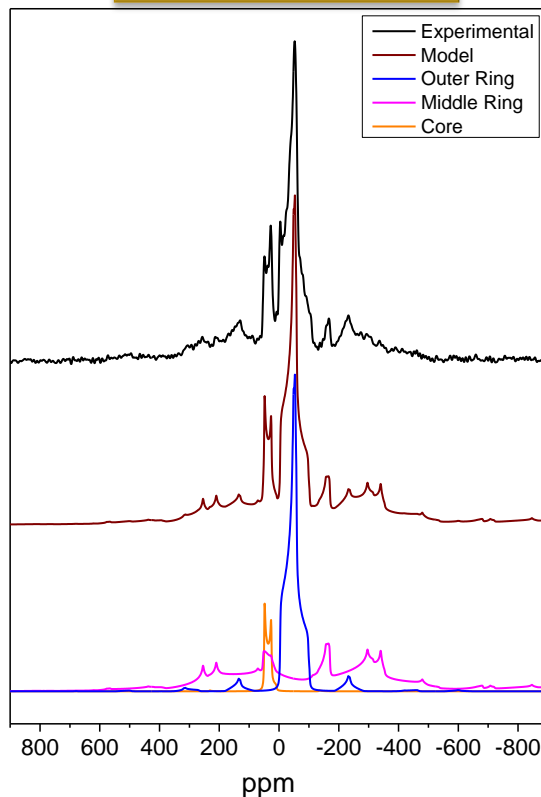
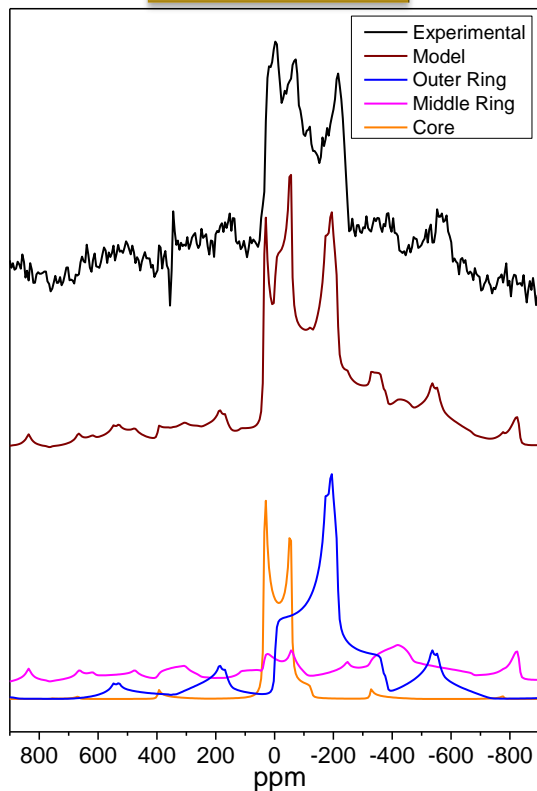
# $^{71}\text{Ga}$ NMR $\text{Ga}_{13}$ Field Dependence



7 Tesla

13.9 Tesla

21.1 Tesla



# Periodic Table of Low $\gamma$ Nuclei

hydrogen 1 H 1.00794																	helium 2 He 4.00260						
lithium 3 Li 6.941	beryllium 4 Be 9.0122																	boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305																	aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.06	chlorine 17 Cl 35.45	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.88	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.38	gallium 31 Ga 69.723	germanium 32 Ge 72.63	arsenic 33 As 74.922	selecnium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80						
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29						
cesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.967	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]					
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnium 110 Uun [271]	ununium 111 Uuu [272]	unubium 112 Uub [277]	ununquadium 114 Uuq [289]										

\* Lanthanide series

\*\* Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.05
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Low  $\gamma$   
High  $\gamma$

<https://www2.warwick.ac.uk/fac/sci/physics/research/condensedmatt/nmr/research/methodologydevelopment/>

# Newly – accessible spin $\frac{1}{2}$ nuclei

Table 1. Nuclei in the region of 0 to 250 MHz at a field corresponding to 1000 MHz proton frequency

Isotope	Symbol	Name	Spin	Natural Abund. % (rel. to $^{13}\text{C}$ )	Receptivity	Magnetic Moment	Gamma (x $10^7$ rad/Ts)	Quadrup. Moment Q/fm <sup>2</sup>	Frequency Reference
187	Os	Osmium	1/2	1.96000	0.00143	0.11198	0.61929	---	22.823 OsO4
103	Rh	Rhodium	1/2	100.00000	0.18600	-0.15310	-0.84680	---	31.864 Rh(acac) <sub>3</sub> p
57	Fe	Iron	1/2	2.11900	0.00425	0.15696	0.86806	---	32.378 Fe(CO) <sub>5</sub>
107	Ag	Silver	1/2	51.83900	0.20500	-0.19690	-1.08892	---	40.478 AgNO <sub>3</sub>
183	W	Tungsten	1/2	14.31000	0.06310	0.20401	1.12824	---	41.664 Na <sub>2</sub> WO <sub>4</sub>
109	Ag	Silver	1/2	48.16100	0.29000	-0.22636	-1.25186	---	46.535 AgNO <sub>3</sub>
89	Y	Yttrium	1/2	100.00000	0.70000	-0.23801	-1.31628	---	49.002 Y(NO <sub>3</sub> ) <sub>3</sub>
169	Tm	Thulium	1/2	100.00000	---	-0.40110	-2.21800	---	82.900
15	N	Nitrogen	1/2	0.36800	0.02250	-0.49050	-2.71262	---	101.368 MeNO <sub>2</sub>
171	Yb	Ytterbium	1/2	14.28000	---	0.85506	4.72880	---	174.993
199	Hg	Mercury	1/2	16.87000	5.89000	0.87622	4.84579	---	179.108 Me <sub>2</sub> Hgr
77	Se	Selenium	1/2	7.63000	3.15000	0.92678	5.12539	---	190.715 Me <sub>2</sub> Se
29	Si	Silicon	1/2	4.68320	2.16000	-0.96179	-5.31900	---	198.672 Me <sub>4</sub> Si
207	Pb	Lead	1/2	22.10000	11.80000	1.00906	5.58046	---	209.206 Me <sub>4</sub> Pb
111	Cd	Cadmium	1/2	12.80000	7.27000	-1.03037	-5.69831	---	212.155 Me <sub>2</sub> Cd
195	Pt	Platinum	1/2	33.83200	20.70000	1.05570	5.83850	---	214.968 Na <sub>2</sub> PtCl <sub>6</sub>
113	Cd	Cadmium	1/2	12.22000	7.94000	-1.07786	-5.96092	---	221.932 Me <sub>2</sub> Cd

# Quadrupolar Periodic Table

IA																	VIIIA
<b>H</b>	IIA											IIIA	IVA	VA	VIA	VIIA	<b>He</b>
Li	Be											<b>B</b>	<b>C</b>	<b>N</b>	<b>O</b>	<b>F</b>	Ne
Na	Mg	IIIB	IVB	VB	VIB	VII B	VIII B			IB	II B	<b>Al</b>	<b>Si</b>	<b>P</b>	<b>S</b>	<b>Cl</b>	Ar
K	Ca	Sc	Ti	V	Cr	Mn	<b>Fe</b>	Co	Ni	Cu	Zn	Ga	Ge	As	<b>Se</b>	Br	Kr
Rb	Sr	<b>Y</b>	Zr	Nb	Mo	Tc	<b>Ru</b>	<b>Rh</b>	Pd	<b>Ag</b>	Cd	In	<b>Sn</b>	<b>Sb</b>	<b>Te</b>	<b>I</b>	Xe
Cs	Ba	La	Hf	Ta	<b>W</b>	Re	Os	Ir	<b>Pt</b>	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Rd	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	<b>Tm</b>	<b>Yb</b>	Lu	
			Th	Pa	<b>U</b>	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Spin =  $\frac{1}{2}$   
Spin >  $\frac{1}{2}$

# Newly-Accessible Quadrupolar Nuclei @ 1 GHz

Isotope	Symbol	Name	Spin	Natural Abund. %	Receptivity (rel. to 13C)	Magnetic Moment	Gamma (x10 <sup>7</sup> rad/Ts)	Quadr. Moment (Q/fm <sup>2</sup> )	Frequency (MHz)
191	Ir	Iridium	3/2	37.3	0.06412	0.1946	0.4812	81.6	17.18
197	Au	Gold	3/2	100	0.16294	0.19127	0.47306	54.7	17.29
235	U	Uranium	7/2	0.72	---	-0.43	-0.52	493.6	18.414
193	Ir	Iridium	3/2	62.7	0.13765	0.2113	0.5227	75.1	18.71
179	Hf	Hafnium	9/2	13.62	0.43824	-0.7085	-0.6821	379.3	25.17
41	K	Potassium	3/2	6.7302	0.03341	0.2774	0.68607	7.11	25.613
167	Er	Erbium	7/2	22.93	---	-0.63935	-0.77157	356.5	28.8
155	Gd	Gadolinium	3/2	14.8	---	-0.33208	-0.82132	127	30.7
145	Nd	Neodymium	7/2	8.3	---	-0.744	-0.898	-33	33.6
161	Dy	Dysprosium	5/2	18.91	---	-0.5683	-0.9201	250.7	34.4
149	Sm	Samarium	7/2	13.82	---	-0.7616	-0.9192	7.4	34.4
73	Ge	Germanium	9/2	7.73	0.64118	-0.97229	-0.93603	-19.6	34.883
83	Kr	Krypton	9/2	11.49	1.28235	-1.07311	-1.0331	25.9	38.476
177	Hf	Hafnium	7/2	18.6	1.53529	0.8997	1.086	336.5	40.07
157	Gd	Gadolinium	3/2	15.65	---	-0.4354	-1.0769	135	40.3
147	Sm	Samarium	7/2	14.99	---	-0.9239	-1.115	-25.9	41.7
87	Sr	Strontium	9/2	7	1.11765	-1.20902	-1.16394	33.5	43.338
105	Pd	Palladium	5/2	22.33	1.48824	-0.76	-1.23	66	45.761
99	Ru	Ruthenium	5/2	12.76	0.84706	-0.7588	-1.229	7.9	46.052
39	K	Potassium	3/2	93.2581	2.8	0.50543	1.25006	5.85	46.664
163	Dy	Dysprosium	5/2	24.9	---	0.7958	1.289	264.8	48.2
173	Yb	Ytterbium	5/2	16.13	---	-0.80446	-1.3025	280	48.21
101	Ru	Ruthenium	5/2	17.06	1.59412	-0.8505	-1.377	45.7	51.614
143	Nd	Neodymium	7/2	12.2	---	-1.208	-1.457	-63	54.5
47	Ti	Titanium	5/2	7.44	0.91765	-0.93294	-1.5105	30.2	56.375
49	Ti	Titanium	7/2	5.41	1.20588	-1.25201	-1.51095	24.7	56.39
53	Cr	Chromium	3/2	9.501	0.50765	-0.61263	-1.5152	-15	56.525
40	K	Potassium	4	0.0117	0.0036	-1.45132	-1.55429	-7.3	58.02
25	Mg	Magnesium	5/2	10	1.57647	-1.0122	-1.63887	19.94	61.216
67	Zn	Zinc	5/2	4.1	0.69412	1.03556	1.67669	15	62.568
95	Mo	Molybdenum	5/2	15.92	3.06471	-1.082	-1.751	-2.2	65.169
201	Hg	Mercury	3/2	13.18	1.15882	-0.72325	-1.78877	38.6	66.116
97	Mo	Molybdenum	5/2	9.55	1.95882	-1.105	-1.788	25.5	66.537
43	Ca	Calcium	7/2	0.135	0.05106	-1.49407	-1.80307	-4.08	67.3
14	N	Nitrogen	1	99.632	5.88235	0.571	1.93378	2.044	72.263
33	S	Sulfur	3/2	0.76	0.10118	0.83117	2.05568	-6.78	76.76
189	Os	Osmium	3/2	16.15	2.32353	0.85197	2.10713	85.6	77.654
21	Ne	Neon	3/2	0.27	0.03912	-0.85438	-2.11308	10.155	78.943
176	Lu	Lutetium	7	2.59	---	3.388	2.1684	497	81.31
37	Cl	Chlorine	3/2	24.22	3.87647	0.8832	2.18437	-6.435	81.557
131	Xe	Xenon	3/2	21.18	3.50588	0.89319	2.20908	-11.4	82.439
61	Ni	Nickel	3/2	1.1399	0.24059	-0.96827	-2.3948	16.2	89.361
91	Zr	Zirconium	5/2	11.22	6.29412	-1.54246	-2.49743	-17.6	92.963
85	Rb	Rubidium	5/2	72.17	45.11765	1.60131	2.59271	27.6	96.549

[www.nyu.edu/cgi-bin/cgiwrap/aj39/NMRmap.cgi](http://www.nyu.edu/cgi-bin/cgiwrap/aj39/NMRmap.cgi)

# Low- $\gamma$ Quadrupolar Periodic Table (Living Systems)

IA																		VIIIA
<b>H</b>	IIA											IIIA	IVA	VA	VIA	VIIA		<b>He</b>
<b>Li</b>	<b>Be</b>											<b>B</b>	<b>C</b>	<b>N</b>	<b>O</b>	<b>F</b>		<b>Ne</b>
<b>Na</b>	<b>Mg</b>	IIIB	IVB	VB	VIB	VII B	VIII B			IB	II B	<b>Al</b>	<b>Si</b>	<b>P</b>	<b>S</b>	<b>Cl</b>		<b>Ar</b>
<b>K</b>	<b>Ca</b>	<b>Sc</b>	<b>Ti</b>	<b>V</b>	<b>Cr</b>	<b>Mn</b>	<b>Fe</b>	<b>Co</b>	<b>Ni</b>	<b>Cu</b>	<b>Zn</b>	<b>Ga</b>	<b>Ge</b>	<b>As</b>	<b>Se</b>	<b>Br</b>		<b>Kr</b>
<b>Rb</b>	<b>Sr</b>	<b>Y</b>	<b>Zr</b>	<b>Nb</b>	<b>Mo</b>	<b>Tc</b>	<b>Ru</b>	<b>Rh</b>	<b>Pd</b>	<b>Ag</b>	<b>Cd</b>	<b>In</b>	<b>Sn</b>	<b>Sb</b>	<b>Te</b>	<b>I</b>		<b>Xe</b>
<b>Cs</b>	<b>Ba</b>	<b>La</b>	<b>Hf</b>	<b>Ta</b>	<b>W</b>	<b>Re</b>	<b>Os</b>	<b>Ir</b>	<b>Pt</b>	<b>Au</b>	<b>Hg</b>	<b>Tl</b>	<b>Pb</b>	<b>Bi</b>	<b>Po</b>	<b>At</b>		<b>Rn</b>
<b>Fr</b>	<b>Rd</b>	<b>Ac</b>																
			<b>Ce</b>	<b>Pr</b>	<b>Nd</b>	<b>Pm</b>	<b>Sm</b>	<b>Eu</b>	<b>Gd</b>	<b>Tb</b>	<b>Dy</b>	<b>Ho</b>	<b>Er</b>	<b>Tm</b>	<b>Yb</b>	<b>Lu</b>		
			<b>Th</b>	<b>Pa</b>	<b>U</b>	<b>Np</b>	<b>Pu</b>	<b>Am</b>	<b>Cm</b>	<b>Bk</b>	<b>Cf</b>	<b>Es</b>	<b>Fm</b>	<b>Md</b>	<b>No</b>	<b>Lr</b>		

Spin =  $\frac{1}{2}$   
Spin >  $\frac{1}{2}$

# Low- $\gamma$ Quadrupolar Periodic Table (Materials)

IA																	VIIIA				
H																	He				
Li	Be															B	C	N	O	F	Ne
Na	Mg	III B	IV B	V B	VII B	VIII B	VIII B			IB	II B	Al	Si	P	S	Cl	Ar				
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr				
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe				
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn				
Fr	Rd	Ac																			
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu					
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr					

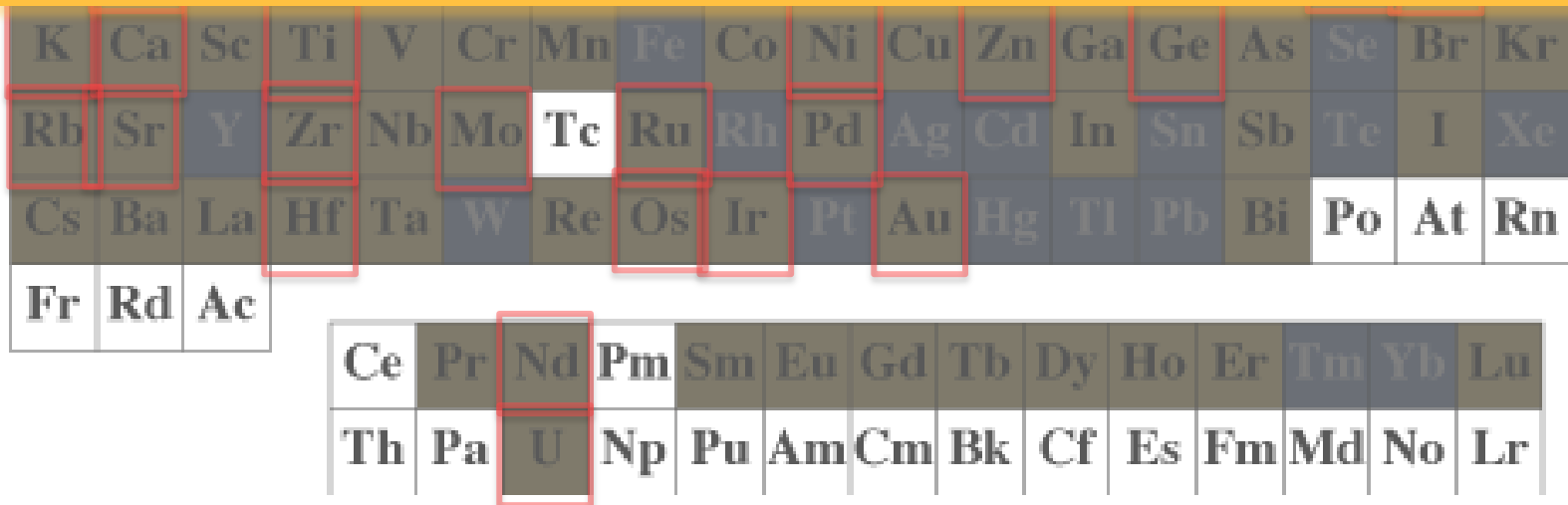
Spin =  $\frac{1}{2}$   
Spin >  $\frac{1}{2}$



# Low- $\gamma$ Quadrupolar Periodic Table

*Let's imagine ... what could be next?*

*What can we study tomorrow that we can't do today?*



K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Rd	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	