NMR and Chemistry
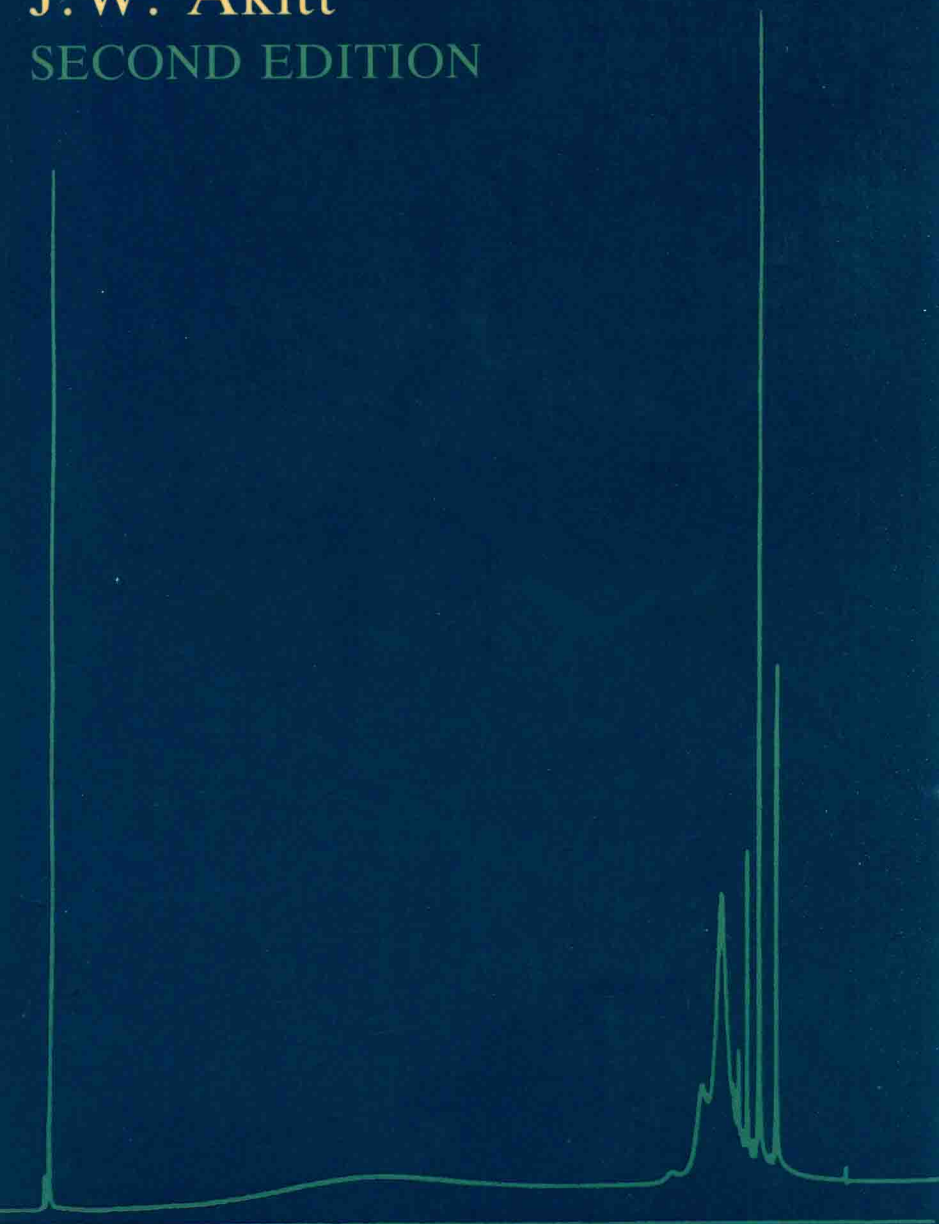
An introduction to the
Fourier transform – multinuclear era

J.W. Akitt

SECOND EDITION

NMR and Chemistry
An introduction to the
Fourier transform–multinuclear era

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Second Edition

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Fourier transform–multinuclear era*

Preface to the First Edition

About 20 years have elapsed since chemists started to take an interest in nuclear magnetic resonance spectroscopy. In the intervening period it has proved to be a very powerful and informative branch of spectroscopy, so much so that today most research groups have access to one or more spectrometers and the practising chemist can expect constantly to encounter references to the technique. There is a considerable number of textbooks available on the subject but these are invariably written primarily either for the specialist or for the graduate student who is starting to use the technique in his research. The author has, however, always felt that a place existed for a non-specialist text written for the undergraduate student giving an introduction to the subject which embraced the whole NMR scene and which would serve as a basis for later specialisation in any of the three main branches of chemistry.

With this in mind the book has been written in two sections. The first covers the theory using a straightforward non-mathematical approach which nevertheless introduces some of the most modern descriptions of the various phenomena. The text is illustrated by specific examples where necessary. The second section is devoted to showing how the technique is used and gives some more complex examples illustrating for instance its use for structure determination and for measurements of reaction rates and mechanisms. A few problems have been included but the main purpose of the book is to demonstrate the many and varied present uses of NMR rather than to teach the student how to analyse a spectrum in detail. This is done best if it is done concurrently with a student's own research.

I am indebted to Dr K. D. Crosbie, Professor N. N. Greenwood, Dr B. E. Mann, and to Professor D. H. Whiffen who read and criticised the

manuscript and to many former colleagues at Newcastle-upon-Tyne for encouragement and for some of the examples used in the text. I also give grateful acknowledgement to Varian Associates Ltd. for permission to reproduced the spectra in Figs 15, 17, 26, 27, 66 and 75 and to Bruker-Spectrospin Ltd. for permission to reproduce the spectra in Figs 49, 50, 63, 64 and 75.

Leeds,   J.W.A.
January, 1972

Preface to the Second Edition

It is just ten years since I wrote the preface to the first edition of this book. The intervening decade has, however, seen such an explosive development of the subject that it has changed almost out of all recognition. Certainly some material has had to be completely replaced by new and the text has had to be extensively rewritten to accommodate current concepts. The first edition contained a mention of Fourier transform techniques, and of superconducting magnets, and these two fields have both developed extremely rapidly because it was realized that they would make possible some real advances in chemical research. The new ^{13}C spectroscopy of organic molecules on the one hand increased the scope of the technique for structural determination, and high field proton spectroscopy on the other enabled the problem of the solution structure of large, biologically important molecules to be tackled. It was also increasingly realized that the Fourier transform pulse techniques allowed precise manipulation of nuclear spins so that many different new relaxation or double resonance experiments became possible. Such advances have also proved to be informative when applied to the less popular nuclei and so multinuclear flexibility was introduced into the new, powerful NMR spectrometers, which can, in principle, carry out most likely experiments with every magnetically active nucleus in the periodic table.

Development has, however, not stopped here. The difficult field of the high resolution study of solid samples is being successfully ploughed; the separation of shift and coupling parameters in a two-dimensional experiment is now possible and the biologists have started to look at somewhat unusual samples such as anaesthetized live rats.

One particularly interesting development which is being vigorously

pursued is that of whole body imaging. It has proved possible to map out the proton density of the water in the body using pulsed NMR techniques in conjunction with specially contoured magnetic fields. This gives a thin cross-section of selected parts of human subjects which can be obtained quickly and safely and gives information which is likely to be complementary to that obtained by X-rays. Thus our technique has expanded and moved into an area which can be seen to be vital to the whole of mankind. Practising spectroscopists will of course be able to point to many areas where NMR has proved invaluable to science and industry, and so to mankind in general. Such advances are unfortunately not immediately obvious to the public at large, and we should welcome the advent of whole body imaging, as a visible testament to the utility of pure science. The physicists who first detected nuclear magnetic resonances are unlikely to have had concern for anything but the details their investigations revealed about the nucleus of the atom. When it became apparent to chemists that the technique was capable of giving uniquely valuable information about the structure of molecules, then their demands led to the development of a spectrometer industry serving academic and industrial science; their quest for higher sensitivity led to the Fourier transform technique and this now is set to lead us into a new medical based industry. Such developments should be well pondered by those who would constrain pure scientific research.

I have left the general plan of the book much as in the first edition; theory, followed by examples of the use of the technique which serve also to reinforce the theory. The technique is approached as primarily a pulse spectrometry but it has proved necessary to retain mention of the old continuous wave methods. Continuous wave equipment is still with us and even the most advanced pulse spectrometer makes use of a continuous wave technique to adjust the magnetic field homogeneity and to provide a field-frequency lock.

Leeds   **J.W.A.**
March 1982

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The Theory of Nuclear Magnetization

1.1 The properties of the nucleus of an atom

The chemist normally thinks of the atomic nucleus as possessing only mass and charge and is concerned more with the interactions of the electrons which surround the nucleus, neutralize its charge and give rise to the chemical properties of the atom. Nuclei however possess several other properties which are of importance to chemistry and to understand how we use them it is necessary to know something more about them.

Nuclei of certain isotopes possess intrinsic angular momentum or spin, of total magnitude $\hbar[I(I+1)]^{1/2}$. The largest measurable component of this angular moment is $I\hbar$, where I is the nuclear spin quantum number and $\hbar$ is the reduced Plancks' constant, $h/2\pi$. I may have integral or half integral values $(0, 1/2, 1, 3/2 \ldots)$, the actual value depending upon the isotope. If $I = 0$ the nucleus has no angular momentum. Since I is quantized, several discrete values of angular momentum may be observable and their magnitudes are given by $\hbar m$, where the quantum number m can take the values $I, I-1, I-2 \ldots -I$. There are thus $2I + 1$ equally spaced spin states of a nucleus with angular momentum quantum number I.

A nucleus with spin also has an associated magnetic moment μ. We can naively consider this as arising from the effect of the spinning nuclear charge which at its periphery forms a current loop. We define the components of μ associated with the different spin states as $m\mu/I$, so that μ also has $2I + 1$ components. In the absence of an external magnetic field the spin states all possess the same potential energy, but take different values if a field is applied. The origin of the NMR

technique lies in these energy differences, though we must defer further
discussion of this until we have defined some other basic nuclear
properties.

The magnetic moment and angular momentum behave as if they
were parallel or antiparallel vectors. It is convenient to define a ratio
between them which is called the magnetogyric ratio, γ.

$$\gamma = \frac{2\pi}{h} \frac{\mu}{I} = \frac{\mu}{I\hbar} \tag{1.1}$$

γ has a characteristic value for each magnetically active nucleus and is
positive for parallel and negative for antiparallel vectors.

If $I > 1/2$ the nucleus possesses in addition an electric quadrupole
moment, Q. This means that the distribution of charge in the nucleus is
non-spherical and that it can interact with electric field gradients arising
from the electric charge distribution in the molecule. This interaction
provides a means by which the nucleus can exchange energy with the
molecule in which it is situated and affects certain NMR spectra
profoundly.

Some nuclei have $I = 0$. Important examples are the major isotopes
^{12}C and ^{16}O which are both magnetically inactive — a fact which leads
to considerable simplification of the spectra of organic molecules. It is
instructive to consider the meaning of zero spin. Such nuclei are free
to rotate in the classical sense and so form a current loop but have no
associated magnetic moment. We must not confuse the idea of quantum
mechanical 'spin' with classical rotation however. The nucleons, that is
the particles such as neutrons and protons which make up the nucleus,
possess intrinsic spin in the same way as do electrons in atoms. Nucleons
of opposite spin can pair, just as do electrons, though they can only
pair with nucleons of the same kind. Thus in a nucleus with even
numbers of both protons and neutrons all the spins are paired and $I = 0$.
If there are odd numbers of either or of both, then the spin is non-zero,
though its actual value depends upon orbital type internucleon
interactions. Thus we build up a picture of the nucleus in which the
different resolved angular momenta in a magnetic field imply different
nucleon arrangements within the nucleus, the number of spin states
depending upon the number of possible arrangements. If we add to this
picture the concept that s bonding electrons have finite charge density
within the nucleus and become partly nucleon in character, then we
can see that these spin states might be perturbed by the hybridization
of the bonding electrons and that information derived from the nuclear

states might lead indirectly to information about the electronic system and its chemistry.

The properties of the most important magnetic isotopes of each element are summarized in Fig. 1.1, which is set out as a periodic table. Each panel of the table contains the spectrometer frequency for a 23.48 kilogauss magnet (2.348 tesla —this field is chosen since it gives a frequency of 100 MHz for ^{1}H), the isotope number of a main active isotope, the spin quantum number I, the nuclear quadrupole moment Q where $I > 1/2$, the natural abundance rounded off to two significant figures, and the receptivity, which is a relative sensitivity figure used to compare signal areas theoretically obtainable at a given magnetic field strength for different nuclei and taking into account both the different magnetic moments and the different natural abundances. Two receptivity figures may be encountered, D^p, the one used here taking ^{1}H as unity, or one relative to ^{13}C for the less receptive nuclei and called D^c. The resonance line heights of nuclei giving resonances of the same width will be in the ratio of these receptivity figures. If more than one isotope of an element has found use in NMR then this is shown by an ‡, except in the case of deuterium, ^{2}H, sometimes written, D, which is important enough to warrant a separate panel of its own.

The usefulness of a nucleus depends in the first place upon the chemical importance of the atom it characterizes and then upon its receptivity. Thus the extreme importance of carbon spectroscopy for understanding the structures of organic molecules has led to technical developments which have overcome the disadvantages of the low receptivity of its magnetically active nucleus, ^{13}C. However, up to quite recently the problems associated with low receptivity had meant that most effort had been expended on relatively few nuclei of high receptivity of which the proton is the most important (proton $\equiv$ ^{1}H — the term proton is commonly used by NMR spectroscopists when discussing the nucleus of neutral hydrogen) since it is a constituent of the majority of organic and many inorganic compounds and gives access to the physical study of diverse systems. Many studies have also been made with boron ^{11}B, for instance in the boron hydrides and carboranes, with fluorine ^{19}F in the vast array of fluoro organics and inorganics and with phosphorus ^{31}P in its many inorganic and biochemical guises. Today, however, the developments which have led to the much more difficult ^{13}C spectroscopy being commonplace mean that virtually the whole of the periodic table is open to study by NMR spectroscopy and many examples will be given in later chapters.

	^{7}Li	^{9}Be		^{1}H	^{2}H	^{3}He
Frequency MHz	38.8	14.0		100.0	15.3	76.2
Spin I	3/2	3/2		1/2	1	1/2
Q	−0.03	0.052		−	0.0027	−
Abundance %	93*‡	100		100	0.015	10^{-4}
receptivity D^P	0.27	1.4×10^{-2}		1	1.5×10^{-6}	5.8×10^{-7}

	^{23}Na	^{25}Mg
Frequency MHz	26.5	6.1
Spin I	3/2	5/2
Q	0.15	0.22
Abundance %	100	10
receptivity D^P	9.3×10^{-2}	2.7×10^{-4}

	^{39}K	^{43}Ca	^{45}Sc	^{47}Ti	^{51}V	^{53}Cr	^{55}Mn	^{57}Fe
Frequency MHz	4.7	6.7	24.3	5.6	26.3	5.6	24.7	3.2
Spin I	3/2	7/2	7/2	5/2	7/2	3/2	5/2	1/2
Q	0.11	0.2	−0.22	0.29	0.04	−0.03	0.55	−
Abundance %	93	0.13	100	7.8	100	9.54	100	2.2
receptivity D^P	4.7×10^{-4}	9.3×10^{-6}	0.301	1.5×10^{-4}	0.381	8.6×10^{-5}	0.175	7.4×10^{-7}

	^{87}Rb	^{87}Sr	^{89}Y	^{91}Zr	^{93}Nb	^{95}Mo	Tc	^{101}Ru
Frequency MHz	32.7	4.3	4.9	9.3	24.4	6.5		4.9
Spin I	3/2	9/2	1/2	5/2	9/2	5/2		5/2
Q	0.13	0.2	−	?	−0.2	0.12		?
Abundance %	27	7	100	11	100	16		17
receptivity D^P	4.9×10^{-2}	1.9×10^{-4}	1.2×10^{-4}	1×10^{-3}	0.482	5.1×10^{-4}		1.7×10^{-4}

	^{133}Cs	^{137}Ba	^{139}La	^{177}Hf	^{181}Ta	^{183}W	^{187}Re	^{189}Os
Frequency MHz	13.1	11.1	14.1	3.0	12.0	4.1	22.8	7.8
Spin I	7/2	3/2	7/2	7/2	7/2	1/2	5/2	3/2
Q	−0.003	0.2	0.21	3	3	−	2.6	0.8
Abundance %	100	11	100	18	100	14	63	16
receptivity D^P	4.7×10^{-2}	8.0×10^{-4}	5.9×10^{-2}	1.2×10^{-4}	3.6×10^{-2}	1.0×10^{-5}	8.6×10^{-2}	3.8×10^{-4}

	Ce	^{141}Pr	^{143}Nd	Pm	^{147}Sm
Frequency MHz		27.0	6.3		3.5
Spin I		5/2	7/2		7/2
Q		−0.059	−0.48		−0.208
Abundance %		100	12		15
receptivity D^P		0.26	3.2×10^{-4}		1.3×10^{-4}

*Of variable abundance either normally or due to commerical separation

Figure 1.1   Table of main naturally occurring magnetically active isotopes. The table shows only one nucleus for each element, but it should be borne in mind that many elements have several magnetically active isotopes. (‡) Some of importance are ^{6}Li, ^{10}B, ^{15}N, ^{37}Cl, ^{79}Br, ^{115}Sn, ^{131}Xe, ^{201}Hg and ^{203}Tl. The NMR frequency in a magnetic field of 23.48 kG (2.348T) is given to the nearest 0.1 MHz. This figure is proportional to the magnetogyric ratio γ. Spin quantum number I,

1.2   The nucleus in a magnetic field

If we place a nucleus in a magnetic field $\mathbf{B_0}$ it can take up $2I + 1$ orientations in the field, each one at a particular angle θ to the field direction and associated with a different potential energy. The energy of a nucleus of magnetic moment μ in field $\mathbf{B_0}$ is $- \mu_z \mathbf{B_0}$, where μ_z is the component of μ in the field direction. The energy of the various

	^{11}B	^{13}C	^{14}N	^{17}O	^{19}F	^{21}Ne
	32.1	25.1	7.2	13.6	94.1	7.8
	3/2	1/2	1	5/2	1/2	3/2
	0.036	—	0.016	−0.026	—	?
	80*‡	1.1*	99.6‡	0.037*	100	0.26
	0.133	1.8×10^{-4}	1.0×10^{-3}	1.1×10^{-5}	0.83	6.3×10^{-6}

	^{27}Al	^{29}Si	^{31}P	^{33}S	^{35}Cl	Ar
	26.1	19.9	40.5	7.7	9.8	
	5/2	1/2	1/2	3/2	3/2	
	0.149	—	—	−0.064	−0.079	
	100	4.7*	100	0.76*	75.5‡	
	0.21	3.7×10^{-4}	6.6×10^{-2}	1.7×10^{-5}	3.6×10^{-3}	

^{59}Co	^{61}Ni	^{63}Cu	^{67}Zn	^{71}Ga	^{73}Ge	^{75}As	^{77}Se	^{81}Br	^{83}Kr
23.6	8.9	26.5	6.3	30.6	3.5	17.1	19.1	27.0	3.9
7/2	3/2	3/2	5/2	3/2	9/2	3/2	1/2	3/2	9/2
0.4	?	−0.16	0.15	0.112	−0.2	0.3	—	0.28	0.15
100	1.2	69*‡	4.1	40‡	7.6	100	7.6	49‡	11.5
0.277	6.3×10^{-4}	6.4×10^{-2}	1.2×10^{-4}	5.6×10^{-2}	1.1×10^{-4}	2.5×10^{-2}	5.3×10^{-4}	4.9×10^{-2}	2.2×10^{-4}

^{103}Rh	^{105}Pd	^{109}Ag	^{111}Cd	^{115}In	^{119}Sn	^{121}Sb	^{125}Te	^{127}I	^{129}Xe
3.1	4.1	4.7	21.2	21.9	37.3	23.9	31.6	20.0	27.7
1/2	5/2	1/2	1/2	9/2	1/2	5/2	1/2	5/2	1/2
—	?	—	—	1.16	—	−0.5	—	−0.7	—
100	22	49	13	96	8.6‡	57	7	100	26‡
3.1×10^{-5}	6.2×10^{-5}	4.9×10^{-5}	1.2×10^{-3}	0.332	4.4×10^{-3}	9.2×10^{-2}	2.2×10^{-3}	9.3×10^{-2}	5.6×10^{-3}

^{193}Ir	^{195}Pt	^{197}Au	^{199}Hg	^{205}Tl	^{207}Pb	^{209}Bi	Po	At	Rn
2.0	21.5	1.7	17.8	57.7	20.9	16.1			
3/2	1/2	3/2	1/2	1/2	1/2	9/2			
1.5	—	0.6	—	—	—	−0.4			
62	34	100	17‡	70‡	21*	100			
2.6×10^{-5}	3.4×10^{-3}	2.5×10^{-5}	9.5×10^{-4}	0.14	2.1×10^{-3}	0.137			

^{151}Eu	^{157}Gd	^{159}Tb	^{163}Dy	^{165}Ho	^{167}Er	^{169}Tm	^{171}Yb	^{175}Lu	^{235}U
24.6	4.0	18.2	3.8	17.0	2.5	8.3	17.7	11.3	1.8
5/2	3/2	3/2	5/2	7/2	7/2	1/2	1/2	7/2	7/2
1.16	2	1.3	1.6	2.82	2.83	—	—	5.7	4.1
48	15	100	25	100	23	100	14	97	0.71*
8.7×10^{-2}	5.0×10^{-5}	3.0×10^{-2}	1.6×10^{-4}	0.10	7.1×10^{-5}	5.7×10^{-4}	7.8×10^{-4}	4.8×10^{-2}	8.5×10^{-7}

quadrupole moment Q in units of $e \times 10^{-24}$ cm^2, approximate abundance and receptivity relative to the proton are also given. For comparison the free electron has spin $\frac{1}{2}$ and a receptivity of 2.8×10^8 since its magnetic moment is 660 times larger than that of the proton. Its resonant frequency would be $\sim$65 600 MHz in the same field, though in practice lower frequencies are used.

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spin states is then:

$$-\frac{m\mu}{I}\mathbf{B_0} \quad \text{or individually} \quad -\mu\mathbf{B_0}, \ -\frac{I-1}{I}\mu\mathbf{B_0}, \ -\frac{I-2}{I}\mu\mathbf{B_0}, \text{etc.}$$

The energy separation between the levels is constant and equals $\mu\mathbf{B_0}/I$. This is shown diagrammatically in Fig. 1.2 for a nucleus with $I = 1$, and positive magnetogyric ratio. The value of m changes sign as it is altered from I to $-I$ and accordingly the contribution of the magnetic moment to total nuclear energy can be either positive or negative, the energy being increased when m is positive. The energy is decreased if the