A Dictionary of Concepts in NMR

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Preface

THE aim of this work is to aid chemists and biochemists familiar with the basic principles of NMR to understand the bewildering array of acronyms and technical jargon which is to be found in the literature. I have chosen a dictionary format since this work is intended to be used as a reference source rather than to be read from cover to cover. In common with present experimental trends, the text is biased heavily towards two-dimensional NMR methods in liquids. These have had a particularly significant impact in studies upon biological systems, and it is hoped that this book will be of particular value to biochemists interested in the inner workings of the experiments and techniques which they routinely use. To this end I have tried to describe the various experiments available to date in particular detail, with cross-reference to the various technical terms where necessary.

I emphasize that I claim no originality for the theoretical framework described here. I have drawn heavily upon the literature of recent years, but have attempted to describe some of the more difficult concepts in a manner which hopefully will be understandable to all who have a basic knowledge of NMR. Although the descriptions are often mathematical, the reader should not recoil from the apparent complexity associated with many of the entries. From personal experience this approach looks more difficult than it really is, and all that is required to understand it is a very rudimentary knowledge of mathematics. The advantage of a quantum mechanical treatment of concepts rather than a simple classical picture, is that one can gain an essentially complete understanding of a given experiment which helps enormously in optimizing it for a given application.

At the end of many entries will be found references for further reading. I have kept these to a minimum, since the purpose of this work is to obviate the need to plough through the original literature in search of a particular concept or technique. Explicit reference in the text is also avoided for the sake of clarity, with apologies to those whose work this approach fails to accredit.

Clearly a work of this size would not have been possible without the contributions of colleagues both past and present. Special thanks are due to Jonathan Boyd, who guided my early interests in NMR, to members of Ray Freeman's research group particularly Chris Bauer, Tom Frenkiel, James Keeler, and David Neuhaus who corrected many misconceptions, and to my colleagues Renzo Bazzo, Iain Campbell, Rino Esposito, Daryl

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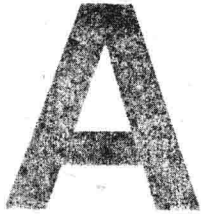

Absolute-value mode The absolute-value mode is defined as the square root of the power spectrum. Thus, if the absorption and dispersion mode components (see **lineshape**) are denoted by U and V respectively, then the absolute-value mode (A) is calculated from

A1 $$A = (U^2 + V^2)^{\frac{1}{2}}.$$

The absolute-value mode was important in two-dimensional NMR before the advent of **phase-sensitive experiments**. Earlier experiments relied upon echo selection to achieve quadrature detection in the ω_1 domain (see **antiecho**), resulting in the appearance of the undesirable (but unavoidable) phase-twist lineshape. This consists of an admixture of absorption mode and dispersion mode lineshapes. The resonance lines in the two-dimensional spectrum can therefore not be adjusted to pure absorption phase. To overcome this difficulty, it is convenient to calculate the absolute-value mode which by definition always has positive intensity. However, since the dispersion-mode component is still present, the ultimate resolution attainable in an absolute-value two-dimensional spectrum is lower than the equivalent phase-sensitive spectrum. In addition, the signal-to-noise ratio is degraded by $\sqrt{2}$. It should be noted that some peaks in spectra derived from certain two-dimensional experiments (e.g. **relayed correlation spectroscopy**) can only be plotted satisfactorily in the absolute-value mode.

Absorption-mode lineshape See **lineshape**.

Aliasing In the conversion of an analogue signal from the NMR receiver to its digital equivalent, the analogue signal is sampled periodically by the **analogue-to-digital converter** (ADC). The sampling theorem states that in order to reproduce faithfully an analogue signal of frequency f, the sampling rate of the ADC is required to be at least $2f$ (see Fig. A1). This is called the Nyquist frequency.

If a signal is present at the ADC input with a frequency which is greater than half the Nyquist frequency, then this signal will nevertheless be digitized but the frequency component of the output signal will apparently differ from that at the input (see Fig. A2). This is known as aliasing. It should be emphasized that this phenomenon differs from a

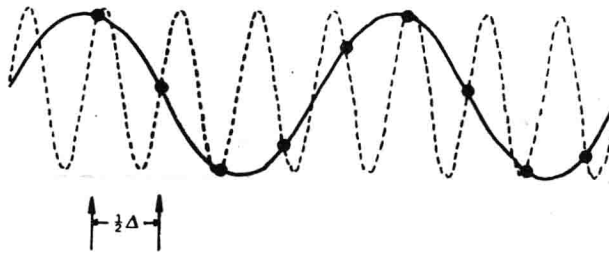

Fig. A1. A sampling rate of 1500 Hz obeys the sampling theorem with respect to the 300 Hz sine wave (solid line). However, the 1200 Hz sine wave (dotted line) is not sampled at an adequate rate and will generate an 'aliased' signal after Fourier transformation (see Fig. A2).

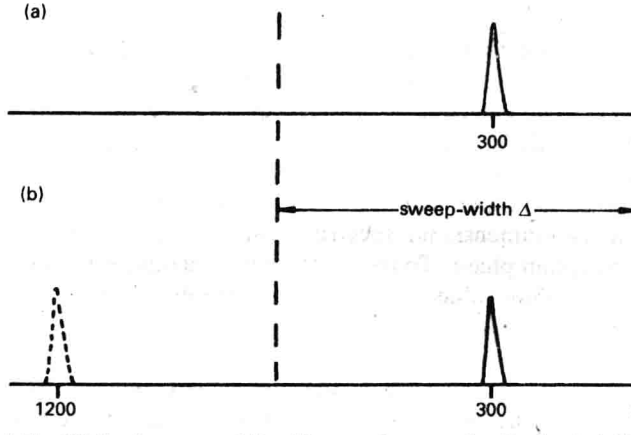

Fig. A2. (a) The 300 Hz sine wave of Fig. A1 generates an authentic signal at 300 Hz. (b) The 1200 Hz sine wave is aliased into the spectrometer sweep-width to generate a spurious signal at 300 Hz.

true frequency shift as generated by, for example, a **phase-sensitive detector**. The effect of aliasing in the NMR spectrum is to generate a resonance line with an anomalous chemical shift. The presence of aliasing is easily detected by altering the **sweep-width** of the spectrometer, when the aliased line will appear to shift. Moreover, aliased resonances often are difficult to phase since their true frequency is usually outside the bandwidth of the **audio-filter** which generally matches the sweep-width. A simple expedient to avoid aliasing is to record a trial spectrum with a large sweep-width such that the sampling frequency is always at least twice that of the largest frequency to be digitized.

Amplifier An amplifier is a device which increases the amplitude of a signal at its input to give a larger signal at its output. In NMR, it is crucial that the

output signal is a faithful reproduction of the input signal, i.e. the amplifier should be distortionless. An ideal amplifer would be a piece of wire with gain. In practice, the devices used to provide amplification invariably introduce some distortion. However, under the correct conditions this can be kept to a very low level. Various types of amplifier can be found in a modern spectrometer, as defined by their operating frequency. Working from the probe inwards, the low-level e.m.f. generated in the receiver coils is amplified to a more tractable level by the spectrometer preamplifier. Since no frequency changing has yet taken place, this preamplifier works at the Larmor frequency (see **Larmor precession**) of the nuclei under investigation which is a radiofrequency (r.f.). For protons, this can be of the order of 600 MHz. In many respects the preamplifier is the most crucial device within the spectrometer, since its properties dictate the overall sensitivity and freedom from spurious effects within the NMR spectrum. In order to achieve the best possible performance, the preamplifier must be capable of amplifying signals with amplitudes of a fraction of a microvolt, i.e. almost on the **noise** level, without introducing any additional noise. Unfortunately, thermal noise within the components of the preamplifier will invariably introduce some additional noise (determined by the **noise figure**), but modern components allow this to be kept to an acceptable level. In addition, the preamplifier is sited as close as possible to the **probe**, in order to reduce signal loss along the connecting cables. Once the signal has been amplified, such stringent requirements can be relaxed in subsequent amplification without significant degradation of the overall signal-to-noise ratio of the spectrometer.

An additional requirement of the preamplifier is its ability to amplify large signals without overload, i.e. it should have a large dynamic range. Any shortcomings here will cause serious distortions in the NMR spectrum of a sample containing an intense resonance line, e.g. a solvent peak (see Hoult (1978)). Of course, this problem can be alleviated by attenuating the input signal to the preamplifier, but this merely degrades the noise figure and is no substitute for a well-designed device.

In most spectrometers, the r.f. signal from the preamplifier is converted to a lower, intermediate frequency (I.F.) by the **phase-sensitive detector**(s). It is then amplified further by the I.F. amplifier(s) which provide most of the overall gain of the spectrometer. The I.F. gain is usually under the control of the experimenter in order to match the output signal of the I.F. amplifier to within the dynamic range of the **analogue-to-digital-converter**. See also **linear amplifier**.

FURTHER READING

For an analysis of amplifier design, see **Hoult, D. I.** (1978). *Prog. NMR Spectr.* **12**, 41–77.

Amplitude modulation The mode of radio transmission known as amplitude modulation is familiar to many from the tuning dials on their radio receivers. In this mode, the amplitude of an r.f. carrier wave is modulated by the information (e.g. speech or music) which it is desired to transmit. Figure A3 illustrates this diagrammatically for a modulating sine wave.

In theoretical terms, the modulation process is represented by the product of the two waveforms. Thus, if the r.f. carrier is represented by $i_c = I_c \cos \omega_c t$ and the modulating cosine wave by $i_m = I_m \cos \omega_m t$ then the resulting signal is described by

A2 $$i = I_c(1 + K \cos \omega_m t) \cos \omega_c t,$$

where $K = I_m/I_c$ is called the modulation depth. By simple trigonometric identity, this can be re-expressed as

A3 $$i = I_c \cos \omega_c t + (KI_c/2) \cos(\omega_c + \omega_m)t + (KI_c/2) \cos(\omega_c - \omega_m)t.$$

In other words, two sidebands are produced which are equidistant by a frequency ω_m from the carrier. It is precisely this mechanism which gives rise to **spinning sidebands** in NMR spectra. A similar situation exists in certain NMR experiments where **density matrix** elements or spin operators are associated with simple sinusoidal or cosinusoidal oscillations in **chemical shifts** or **spin couplings**. As an example, the term $I_x \cos \omega_I t$ which represents x magnetization of spin I modulated by the **Larmor precession** frequency of spin I, can be thought of as an amplitude modulation. Using the identity $\cos x = \frac{1}{2}[\exp(ix) + \exp(-ix)]$, it is seen that an amplitude-modulated function can be decomposed into a sum of phase modulated signals (see **phase modulation**). On **Fourier transformation**, the frequency-domain signal $S(t) = \frac{1}{2}[\text{Abs}(\omega_x) + i\,\text{Dis}(\omega_x) + \text{Abs}(-\omega_x) + i\,\text{Dis}(-\omega_x)]$, where Abs and Dis represent the absorption-mode and dispersion-mode lineshapes (see **lineshape**). The real part of this function (the detected signal), $\frac{1}{2}[\text{Abs}(\omega_x) + \text{Abs}(-\omega_x)]$,

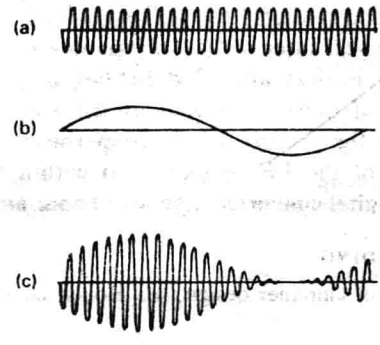

Fig. A3. (a) A sine wave. (b) A low-frequency modulating signal. (c) The sine wave (a) amplitude modulated by (b).

shows that there is no sign discrimination of the Larmor precession frequency, and two resonance lines will be found on either side of the transmitter reference frequency. In **two-dimensional NMR**, it is important to obtain sign discrimination in both dimensions, which can be achieved by either using phase modulation, or more usefully by so-called **phase-sensitive experiments**.

FURTHER READING

Keeler, J. and Neuhaus, D. (1985). *J. Magn. Reson.* **63**, 454.

Analogue-to-digital converter (ADC) In Fourier transform NMR, all post-acquisition data manipulation is performed using digital computers. The very low-level e.m.f. generated in the receiver coils by the sample is first amplified (see **amplifier**), and then converted to a lower frequency signal by a **phase-sensitive detector**. This low-frequency (**audio-frequency**) signal is of course an analogue signal, i.e. it varies continually with time. It must therefore be digitized before it can be handled by the computer. This is achieved by an **analogue-to-digital converter**, or ADC. Of particular importance in NMR of biological molecules is the dynamic range of the ADC. That is, the ability of the ADC to digitize weak signals faithfully in the presence of strong signals. This ability is dependent upon the wordlength of the ADC. We often refer to '12-bit ADCs' or '20-bit ADCs'. This simply means that the wordlength which characterizes the ADC is 12 or 20 bits. The largest integer that can be registered in a single computer word will therefore be $2^{12} - 1 = 4095$ or $2^{20} - 1 = 1\,048\,575$. If the ratio of the intensities of the strongest and weakest signals is greater than either 4095 or 1 048 575, then the input data will exceed the dynamic range of the ADC, and the small signal will not be digitized accurately. Bearing in mind that the concentration of protons in H_2O is 110 M, and that often NMR studies of macromolecules in 90% H_2O/10% D_2O are performed at concentrations of a few mM, it can be seen that a high-quality ADC is required. In practice the required fidelity is reduced by irradiation of the H_2O resonance (see **solvent suppression**). In other experiments in D_2O, the signal-to-noise ratio is often quite poor, and under these circumstances the precision of digitization can be much lower since the dynamic range is low. In some circumstances, the use of a lower ADC resolution is valuable, since a larger number of transients can be co-added without overflowing the available wordlength. Thus, an ADC resolution of 10 bits on a 20-bit wordlength computer allows 1024 experiments to be accommodated, but with an ADC resolution of 16 bits, only 16 experiments can be accommodated. Alternatively, double-precision arithmetic can be employed, whereby two computer words are used for one integer.

Angular momentum The studies of Bohr on the spectrum of the hydrogen atom introduced the postulate that the angular momentum of a system was quantized, i.e. it could only take values which were integer multiples of $h/2\pi$, where h is Planck's constant. Several years later it was suggested by Sommerfeld that the directions of orientation of the electronic angular momentum vector were restricted to certain orientations when the electron was in a closed orbit. In other words, the direction as well as the magnitude of the angular momentum vector was quantized.

In classical mechanics the angular momentum of a particle about a fixed point x is given by

A4 $$I = r \times P$$

where r is the position vector of a particle with respect to x, and P is the linear momentum..

In quantum mechanics the components of position and linear momentum of a particle obey the commutation relations (see **commutator**)

A5 $$[r_n, P_m] = i\delta_{nm}$$

A6 $$[r_n, r_m] = 0$$

A7 $$[P_n, P_m] = 0$$

$$n, m = x, y, z$$

where $\delta_{nm} = 1$ if $n = m$ and is zero otherwise. We can apply these relations to find the commutation rules for the components of angular momentum I_x, I_y, I_z:

A8 $$I_x = (r_y P_z - r_z P_y)$$

A9 $$I_y = (r_z P_x - r_x P_z)$$

A10 $$I_z = (r_x P_y - r_y P_x).$$

Thus, for example,

A11
$$\begin{aligned}[I_x, I_y] &= (r_y P_z - r_z P_y)(r_z P_x - r_x P_z) - (r_z P_x - r_x P_z)(r_y P_z - r_z P_y) \\ &= r_y P_x (P_z r_z - r_z P_z) + r_x P_y (r_z P_z - P_z r_z) \\ &= i(r_x P_y - r_y P_x) \\ &= i I_z.\end{aligned}$$

A similar procedure for the other combinations gives the full commutation relations:

A12 $$[I_x, I_y] = iI_z$$

A13 $$[I_y, I_z] = iI_x$$

A14 $$[I_z, I_x] = iI_y.$$

The non-commutation of the components of angular momentum is a consequence of quantization. The **uncertainty principle** therefore makes it impossible to measure simultaneously the values of any two components of angular momentum. A further consequence of quantization is that the total angular momentum of a nucleus can take only discrete values, namely $[I(I+1)]^{\frac{1}{2}}\hbar$, where $\hbar = h/2\pi$ and I is the spin quantum number or 'spin', which has half-integral values. The observable magnitudes of a given component of the angular momentum are expressed in terms of the magnetic quantum number m, e.g. $I_z = m\hbar$, where $m = I, (I-1), (I-2), \ldots -I$, giving $(2I+1)$ values. This expression for m is consistent with the selection rule that $\Delta m = \pm 1$. Thus if $I = \frac{1}{2}$ (as for protons) then there are two values of m, $\pm\frac{1}{2}$, and two possible values of I_z, $\pm\frac{1}{2}\hbar$.

The commutation relations in (A12)–(A14) define the components of spin angular momentum as a set of spin angular momentum **operators**. If we consider a spin $\frac{1}{2}$ system described by the **orthonormal** wave functions $|\alpha\rangle$ and $|\beta\rangle$ (expressed in the **bra-ket notation**), then the operators I_x, I_y, and I_z behave as follows:

A15
$$
\begin{aligned}
I_x|\alpha\rangle &= \tfrac{1}{2}|\beta\rangle \\
I_x|\beta\rangle &= \tfrac{1}{2}|\alpha\rangle \\
I_y|\alpha\rangle &= \tfrac{1}{2}\mathrm{i}|\beta\rangle \\
I_y|\beta\rangle &= -\tfrac{1}{2}\mathrm{i}|\alpha\rangle \\
I_z|\alpha\rangle &= \tfrac{1}{2}|\alpha\rangle \\
I_z|\beta\rangle &= -\tfrac{1}{2}|\beta\rangle.
\end{aligned}
$$

Here, the **eigenvalues** of I_z, $\frac{1}{2}$ and $-\frac{1}{2}$, in units of $\hbar$ correspond exactly to the two values of m. In general, the various **Hamiltonians** under which spin systems evolve in NMR experiments can be formulated in terms of I_x, I_y, and I_z. These operators are therefore of fundamental importance for the quantum mechanical description of NMR and (A12)–(A15) form the basis of this description. The **matrix representations** of I_x, I_y, and I_z are the well-known **Pauli-spin matrices**.

FURTHER READING

The following texts describe the quantum mechanical principles of angular momentum in detail:

Edmonds, A. R. (1974). *Angular momentum in quantum mechanics*, (2nd edn). Princeton University Press, Princeton.

Rose, M. E. (1957). *Elementary theory of angular momentum*. Wiley, New York.

Angular momentum operators See **angular momentum.**

Anisotropic chemical shift relaxation The chemical shift of a nucleus is dependent upon the orientation of the molecule in a magnetic field.

Rapid molecular motions in liquid state result in an **averaging** of all possible values, resulting in an average chemical shift which is the trace (see Appendix 3) of the chemical shielding **tensor**:

A16 $$\sigma = \tfrac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz}).$$

On a shorter time-scale the nucleus experiences fluctuations in the local magnetic field, and if the chemical shielding tensor is anisotropic (i.e. $\sigma_{xx} \neq \sigma_{yy} \neq \sigma_{zz}$), then this provides a relaxation mechanism. The relaxation rate is dependent upon the **Larmor precession** frequency ω, upon the molecular **correlation time** τ_c, and upon the magnitude of the static field B_0:

A17 $$\frac{1}{T_1} = \frac{1}{15}\gamma^2 B_0^2(\sigma_{\parallel} - \sigma_{\perp})^2 \cdot \frac{2\tau_c}{1 + \omega^2 \tau_c^2}$$

A18 $$\frac{1}{T_2} = \frac{1}{90}\gamma^2 B_0^2(\sigma_{\parallel} - \sigma_{\perp})^2 \left[\frac{6\tau_c}{1 + \omega^2 \tau_c^2} + 8\tau_c\right]$$

where γ is the **magnetogyric ratio** and $\sigma_{\parallel}$ and $\sigma_{\perp}$ refer to shielding along and perpendicular to the symmetry axis, assuming axial symmetry. In the **extreme narrowing** limit, (A17) and (A18) reduce to

A19 $$\frac{1}{T_1} = \frac{2}{15}\gamma^2 B_0^2(\sigma_{\parallel} - \sigma_{\perp})^2 \tau_c$$

A20 $$\frac{1}{T_2} = \frac{7}{45}\gamma^2 B_0^2(\sigma_{\parallel} - \sigma_{\perp})^2 \tau_c$$

and T_1 does not equal T_2 under extreme narrowing conditions, in contrast to the situation under exclusive dipole–dipole **relaxation**.

FURTHER READING

Abragam, A. (1961). *The principles of nuclear magnetism*, Chapter 8. Clarendon Press, Oxford.

Anisotropic motion In **relaxation** theory, the **autocorrelation function** characterizes the type of molecular motion responsible for the relaxation. A particularly simple assumption is that the correlation function is an exponential with a time constant equal to the **correlation time** τ_c. This is a reasonable assumption for certain types of motion, for example rotation of a spherical molecule. In the case of other types of motion, for example relaxation caused by random translational diffusion, the correlation function cannot be represented adequately by a single exponential. Another complication which is of particular importance in biological NMR is the possibility of a distribution of correlation times caused by internal motion. In other words, motion within the macromolecule

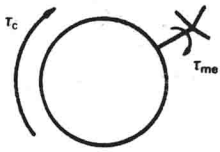

Fig. A4. Diagrammatic representation of a methyl group anisotropically rotating on a globular macromolecule. The correlation times are denoted by τ_{me} and τ_c respectively.

cannot be described by a single correlation time. In such cases the correlation function may again be non-exponential, and a suitable model for the anisotropic motion must be derived.

One example which has been studied in great detail is the rotation of a methyl group on the surface of a protein. The spectral density function (see **relaxation**) for the anisotropic rotation of the internuclear vector between two spins in the methyl group has been derived on the assumption that the methyl group rotates around a spinning axis on the globular protein (Fig. A4). Two correlation times must thus be considered: first, the correlation time characterizing the (fast) spinning of the methyl group about the spinning axis (τ_{me}), and secondly the isotropic reorientation of the spinning axis, which can be assumed to be identical to the rotational correlation time of the macromolecule (τ_c). Under these conditions the spectral densities have been calculated by Woessner:

A21 $$J(0) = \tfrac{1}{4} \cdot \tau_c + \tfrac{3}{4} \cdot \tau_r$$

A22 $$J(\omega) = \frac{1}{4} \cdot \frac{\tau_c}{1+\omega^2\tau_c^2} + \frac{3}{4} \cdot \frac{\tau_r}{1+\omega^2\tau_r^2}$$

A23 $$J(2\omega) = \frac{1}{4} \cdot \frac{\tau_c}{1+4\omega^2\tau_c^2} + \frac{3}{4}\frac{\tau_r}{1+4\omega^2\tau_r^2}$$

where ω is the Larmor frequency of the methyl protons, $1/\tau_r = 1/\tau_c + 1/\tau_{me}$ for a model involving jumping of the methyl group between three sites, and $1/\tau_r = 1/\tau_c + 4/\tau_{me}$ for a diffusional model. The correlation time τ_{me} is that characterizing the methyl group rotation. The magnitudes of the **spin–lattice relaxation** rate ($1/T_1$) and the **spin–spin relaxation** rate ($1/T_2$) can be computed in the usual way from these equations. Although the decay of both longitudinal and transverse magnetization is predicted to be a simple exponential, this is not always found to be the case experimentally. The discrepancy arises from the fact that cross-correlation of proton pairs has been neglected in the Woessner theory, i.e. the motion of each methyl proton is assumed to be uncorrelated with its neighbours. However, this assumption is not justified in certain cases and cross-correlation gives rise to deviations from simple exponential behaviour. A theoretical formalism which includes cross-correlation effects has been described by Werbelow and Marshall. This treatment

predicts that the decay of longitudinal magnetization shows nearly exponential behaviour, whereas the decay of transverse magnetization is strongly non-exponential, and is in fact composed of a sum of three exponentials. This is reflected in the lineshapes of methyl groups anisotropically rotating on large proteins, which in general are composed of a broad component, and a narrow component which in turn is a superposition of two Lorentzians. The exact shape depends upon ω, τ_c, and τ_{me}.

FURTHER READING

Werbelow, L. G. and Marshall, A. G. (1973). *J. Magn. Reson.* **11**, 299.
Woessner, D. E. (1962). *J. Chem. Phys.* **36**, 1.
A detailed discussion of the effect of internal motion in proteins can be found in
Kalk A. and Berendsen, H. J. C. (1976). *J. Magn. Reson.* **24**, 343.

Anisotropy Anisotropy is manifest in an NMR spectrum when certain components of the **Hamiltonian** of the system do not average to zero. In NMR of liquids, certain components average naturally due to random reorientation in ordinary coordinate space. In fact only scalar chemical shifts and scalar indirect spin–spin couplings survive. These are the interactions which cause the structures of high-resolution NMR spectra. Where molecules have restricted motion, i.e. in nematic liquids and solids, such averaging does not occur, and additional components of the Hamiltonian contribute to the spectrum (see **powder spectrum**). Examples are dipolar couplings and magnetic shielding. These have an orientation-dependence of the spins with respect to the applied field. In favourable circumstances such anisotropies can be averaged in ordinary coordinate space (see **magic-angle spinning**) or in **spin space**.

FURTHER READING

Haeberlen, U. (1976). High resolution NMR in solids. *Adv. Mag. Reson. suppl.* 1.

Antiecho In the absence of **phase cycling**, most **two-dimensional NMR** experiments are associated with **amplitude modulation** of **magnetization** during the t_1 period. An amplitude-modulated signal, given for example by $\cos(\omega_1 t)$ can be decomposed into a sum of phase-modulated signals, since $\cos(\omega_1 t) = \frac{1}{2}(\exp(i\omega_1 t) + \exp(-i\omega_1 t))$. After **two-dimensional Fourier transformation**, signals are found at $\pm\omega_1$ (see **amplitude modulation**). Therefore, unless the **carrier** is displaced to one side of the spectrum, signal overlap will result. In order to avoid this problem, the signs of the ω_1 frequencies must be discriminated. A common approach has been to convert the modulation of the signals during t_1 to one of phase (see **phase modulation**). This is achieved by phase cycling the

receiver reference and all pulses preceding t_1 (transmitter phase shift) by $\pi/2$ radians (or $\pi/2n$ for n-quantum experiments). If the phase shifts are in the same sense, signals are detected with identical signs in ω_1 and ω_2, whereas if the phases are cycled in the opposite sense, signals are detected having apparent signs of precession frequencies in ω_1 opposite to those in ω_2. The former signals are known as antiecho or P-type peaks, while the latter are known as echo or N-type peaks. Each type of signal has the undesirable phase-twist lineshape, and ω_1 discrimination can be achieved in a more satisfactory manner using **phase-sensitive experiments**. The key principle to the mechanism of, for example echo selection, is the detection of a second amplitude-modulated component (see **amplitude modulation**) (resulting from the transmitter phase shift) which has sine rather than cosine modulation. Addition of the sine and cosine modulated signals, together with the receiver reference phase shift, results in the time-domain signal

$$\begin{aligned} S(t_1, t_2) &= \cos(\omega_1 t_1)\exp(i\omega_2 t_2) \\ &\quad + \exp(i\pi/2)\sin(\omega_1 t_1)\exp(i\omega_2 t_2) \\ &= \exp(i\omega_1 t_1)\exp(i\omega_2 t_2). \end{aligned} \qquad \text{A24}$$

Upon Fourier transformation in both dimensions, the real part (see **complex number**) of the spectrum is a single phase-twist line at $+\omega_1$, $+\omega_2$:

$$\mathrm{Re}[S(\omega_1, \omega_2)] = (\mathrm{Abs}\,\omega_1^+\,\mathrm{Abs}\,\omega_2^+ - \mathrm{Dis}\,\omega_1^+\mathrm{Dis}\,\omega_2^+). \qquad \text{A25}$$

FURTHER READING

Keeler, J. and Neuhaus, D. (1985). *J. Magn. Reson.* **63**, 454.

Apodization See **convolution**.

Audio-filter Before the **audio-frequency** signal derived from the final detector in an NMR **spectrometer** is digitized (see **analogue-to-digital converter**), it undergoes a stage of audio-filtration. The sampling theorem shows that in order to reproduce faithfully a waveform of frequency f, the sampling rate of the ADC must be $2f$, i.e. twice per cycle (see **aliasing**). If the offset of the most distant resonance line from the **carrier** is known, then it is a simple matter to ensure that the sampling rate is sufficiently high to allow each resonance to be recorded with its true **Larmor precession** frequency. This is in fact achieved automatically when the **sweep-width** of the spectrometer is adjusted. However, although there may be no signals present at greater than f, **noise** will certainly be present, and since the sampling rate is fixed at $2f$, this noise will be aliased into the spectrum. Degradation of the signal-to-noise ratio will therefore result. To prevent this, the signal is stripped of any significant noise above f by