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Chemical applications of high-resolution ^{13}C n.m.r. spectra for solids

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^{13}C n.m.r. experiments are described that use the dipolar decoupling, cross-polarization and magic angle rotation techniques with a home-built spectrometer system. The subsidiary experimental methods of (*a*) spin-echo Fourier transform, (*b*) magnetization flip-back, (*c*) non-quaternary suppression and (*d*) single-pulse excitation are mentioned, and the equipment is briefly described.

Applications of the methods are presented that have involved organic compounds, polymeric materials and inorganic systems. Discussion centres on special features of solid state spectra such as (*a*) multiplicity of crystallographic sites, (*b*) chemical shift and bandwidth differences from solution state spectra, and (*c*) effects of coupling to heteronuclei. Emphasis is placed on the value of the experiments for structural chemistry, as in cases of tautomerism, polymorphism and hindered intramolecular motion.

1. Introduction

The techniques necessary for obtaining high-resolution n.m.r. spectra of dilute spins (such as ^{13}C) in solid samples are now reasonably well established, though significant improvements during the next 3 or 4 years are likely. Now that commercial instruments for implementing these techniques are available, a rapid growth in their application to chemical problems may be expected. However, at present relatively few research papers on this topic have been published; most of the reports of work in this area to date concentrate either on the techniques themselves or on investigations of a more physical nature. Consequently, the aim of this paper is to present, at a qualitative and illustrative level, a broad discussion of the chemical information that may be derived from high-resolution dilute-spin n.m.r. spectra of solids, mainly by using examples from work in our own laboratory. Since the popularity of the techniques will be dominated by ease of sample handling, it is clear that most chemical applications will involve powders, polycrystalline samples and amorphous materials, so this paper will be restricted to such situations. Moreover, to put a limit to the discussion, we shall only consider spectral features involving isotropic chemical shifts, splittings and band shapes. Relaxation properties will not be dealt with *per se*, though they greatly influence the way in which spectra are acquired and their measurement yields much valuable physicochemical information (VanderHart & Garroway 1979; Garroway *et al.* 1979; Schaefer *et al.* 1975, 1977; Stejskal *et al.* 1978).

Since the impetus for the use of the techniques is provided by the desire to obtain spectra analogous to those for isotropic solutions, it is not surprising that many of the applications will be obvious to chemists with experience of solution-state n.m.r. However, the nature of the solid state dictates that the spectra can be subtly different from those for solutions, and herein lies much of the interest. There are also a few features in the spectra themselves that depend on differences in the behaviour of spin systems in solids and solutions. It is not easy to entirely

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separate these strands of interest but, after a description of our experimental arrangement and of the techniques used, our discussion of applications will be divided into three main areas: the effects of molecular enviroment, chemical effects on shielding constants and line widths, and the influence of other nuclei.

High-resolution n.m.r. spectroscopy of the solid state provides interesting information regardless of the solubility or insolubility of the sample. Although we specifically mention insoluble materials in §4*a* below, this is merely to emphazise the increase in the range of applicability of high-resolution n.m.r. It is arguable that work in solids may become preferred to solution-state n.m.r. for many compounds, even when they are soluble (the 'concentration', and hence in principle the sensitivity, is clearly maximum for a pure solid sample). However, it is likely that in most cases, solution-state and solid-state work may yield complementary information. In combination they allow the investigation of medium effects (including the compound itself as the medium, as for a pure solid or melt).

Although this article deals only with ^{13}C-{^{1}H} spectra, the methods are also suitable for observation of other dilute spins, such as ^{15}N, ^{29}Si and ^{119}Sn (Lippmaa *et al.* 1978).

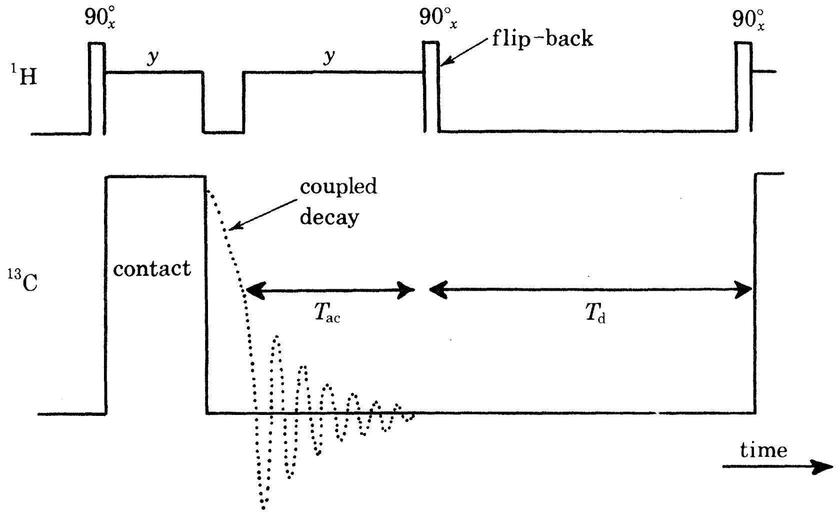


FIGURE 1. The pulse sequence for cross-polarization ^{13}C n.m.r. spectra, including the non-quaternary suppression and flip-back procedures (though these are never implemented together in the same experiment). During the contact pulse the Hartmann–Hahn (1962) condition, $\gamma_H B_2(^1H) = \gamma_C B_1(^{13}C)$, must be met. The acquisition and delay (recycle) times are indicated T_{ac} and T_d respectively.

2. EXPERIMENTAL PROCEDURES

Our basic mode of operation conforms to the pattern now established for high-resolution dilute-spin spectra of solids, that is we use:

(i) high-power (dipolar) decoupling of the abundant spins (protons) to eliminate (^{13}C, ^{1}H) dipolar interactions as a source of broadening in the ^{13}C spectra;

(ii) cross-polarization (c.p.) between ^{1}H and ^{13}C systems by heteronuclear double resonance under the Hartmann–Hahn condition, so as to overcome sensitivity problems associated with long ^{13}C spin–lattice relaxation times (figure 1 shows the pulse sequence used, including some special features to be discussed below);

(iii) magic angle rotation (m.a.r.) (Andrew 1971) to reduce shielding constants (and scalar heteronuclear coupling constants) to their isotropic averages, and to eliminate homonuclear (^{13}C, ^{13}C) dipolar interactions (and weak dipolar interactions of ^{13}C to heteronuclei other than ^{1}H).

Efficient investigation of the ^{13}C spectra requires appropriate adjustment of the various time intervals in the cross-polarization procedure. The optimum values of these intervals depend on the proton relaxation times T_1 and $T_{1\rho}$, which can vary widely for different materials. For a rigid crystalline solid T_1 and $T_{1\rho}$ may be as long as minutes, while in other situations $T_{1\rho}$'s less than 1 ms may be encountered. The worst combination from the point of view of c.p. experiments is a short $T_{1\rho}$ associated with a very long T_1. Except sometimes when a closely related series of molecules is being examined, we therefore find it extremely important to determine the values of $T_1(^{1}\mathrm{H})$ and $T_{1\rho}(^{1}\mathrm{H})$ before attempting to obtain ^{13}C spectra. It is not, however, necessary to determine the proton relaxation parameters accurately. Sometimes it is desirable to run static ^{13}C c.p. spectra, to optimize the experimental variables before proceeding to use m.a.r. All the spectra illustrated in this article were obtained under conditions of dipolar decoupling, cross-polarization and magic angle rotation unless stated otherwise.

The chemicals studied in the investigations reported here were all obtained as gifts (see the acknowledgements) or were available commercially. They were all used without additional purification, except for 2,4-dinitrotoluene, which was recrystallized from ethanol. Chemical shifts are reported with respect to the signal of $\mathrm{Me_4Si}$.

We have found certain variations on the basic experiments (i)–(iii) listed above to be valuable in some cases; these will be described briefly here.

(*a*) *Spin–echo Fourier transform operation*

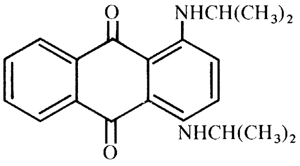
After the contact pulse of the c.p. sequence, the spectrometer takes some time (*ca.* 100 μs) to recover and to record the magnetization properly. Consequently the first few points in the free induction decay (f.i.d.) may have distorted values. This can lead to a baseline roll in the spectrum, which is particularly noticeable for broad lines (owing to the loss of a substantial proportion of the f.i.d.) and results in considerable uncertainty in the distribution of spectral intensity, making visual phase adjustments rather arbitrary. The use of a 180° refocusing pulse at time τ after the end of the contact pulse results in an echo at time 2τ as the f.i.d. is normally dominated by the inhomogeneous shielding interaction (Pines & Shattuck 1973). If data acquisition begins at 2τ, an undistorted set of points is obtained, which eliminates the baseline problems. This technique is usually referred to as spin-echo Fourier transform (s.e.F.t.) operation, and works well for static samples. However, problems arise for m.a.r. spectra because of the requirement for maximum echo formation that the experience of the spin system during the time τ to 2τ be identical to that between 0 and τ. During these time intervals the spins sample *part* of the shielding range caused by shielding anisotropy, depending on the orientation of the particle in B_0 at time zero, on the duration τ, and on the angle through which rotation has occurred in time τ. At rotation rate ω_r this rotation angle is $\omega_r\tau$, typically *ca.* 2 rad in our experiments. This implies that the experience of the spins during the interval 0 to τ differs from that during the period τ to 2τ, and imperfect refocusing will result, giving signals of lower peak height. The effect will be particularly marked for carbon nuclei with large shielding anisotropies. Therefore, unless the rotation period can be synchronized with the time τ, the s.e.F.t. method should be avoided when accurate work is required. Fortunately, m.a.r. spectra do not suffer from baseline problems to the same degree as static spectra since the f.i.d. lasts considerably longer and hence the system recovery is less significant.

(*b*) *Flip-back*

When the proton spin–lattice relaxation times in the laboratory and rotating frames (T_1 and $T_{1\rho}$ respectively) are both long, it is advantageous to use *multiple-contact* cross-polarization (Pines *et al.* 1973). Unfortunately, this procedure requires the proton r.f. field to be active for a long time, and substantial problems of heat dissipation may result. Recently, Tegenfeldt & Haeberlen (1979) have introduced a pulse sequence giving the opportunity for a holding time during which the proton r.f. field is off. The process involves flipping the proton magnetization back into the $z(B_0)$ direction immediately that acquisition of the carbon f.i.d. is completed (figure 1). A delay time, T_d, ensues before the next cross-polarization cycle is commenced. The value of T_d can be adjusted to the minimum consistent with the avoidance of heat dissipation problems provided the ratio $T_1(^1H)/T_{1\rho}(^1H)$ is reasonably favourable. As a bonus, the z magnetization of the protons will grow back towards the Boltzmann equilibrium value during T_d. We have found this technique very valuable. A typical case is 2,4-dinitrotoluene, which has $T_1(^1H) = 16$ s, $T_{1\rho}(^1H) > 1$ s; we have obtained good spectra with $T_d = 3$s for an acquisition time $T_{ac} = 66$ ms.

(*c*) *Non-quaternary suppression*

Any experiment that assists in spectral interpretation is to be welcomed, and one that leads to the identification of signals due to quaternary carbons can be particularly valuable. In solution-state ^{13}C n.m.r. this can be accomplished by off-resonance or low-power proton decoupling. Such methods are unsuitable for solids, but a similar result can be achieved by the delayed-acquisition experiment proposed by Opella & Frey (1979) (figure 1). In this experiment a delay time is introduced between the contact pulse and acquisition of the f.i.d., during which the proton r.f. is gated off. In this interval the carbon f.i.d. is dominated by the carbon–proton dipolar couplings. Provided carbon spin diffusion is slow, each chemically shifted carbon will respond independently to its own dipolar local fields. Such local fields will be orders of magnitude smaller for quaternary carbons than for others, and if a suitable delay time is chosen the magnetization of non-quaternary carbons will have decayed virtually to zero whereas the quaternary magnetization will be little affected, We have found this non-quaternary suppression (n.q.s.) experiment to be extremely discriminating when a delay time of *ca.* 40 μs is used. Figure 2 illustrates the power of this technique. Substantial thermal motion can also reduce carbon second moments sufficiently to yield residual signals under the operation of the n.q.s. experiment, and this is particularly common for methyl groups, as is shown in figure 2 for the anthraquinone derivative **1**. A study of the variation of peak intensities as a function of the pre-acquisition delay gives selective information about proton-coupled carbon second moments.



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(*d*) *Single-pulse excitation*

There are many chemical situations where the material is neither entirely rigid nor entirely mobile, for instance biochemical systems or polymers. In these cases, full information cannot be obtained by a single type of n.m.r. experiment. We have frequently encountered this situation in the polymer area, where the sample may be macroscopically rigid but where on the molecular scale the mobility varies for different regions. Consequently it is essential to use not only the c.p. experiment but also the traditional solution-state F.t. n.m.r. mode of operation, with one modification, namely the use of high power levels in the proton channel to give dipolar decoupling. The latter experiment is characterized by its being initiated with a single pulse (in the carbon channel), proton power only being added to secure decoupling. For convenience we shall refer to this as the single-pulse excitation (s.p.e.) experiment. It is important, to achieve optimum signal:noise for solid state spectra, to adjust the contact time critically when in the c.p. mode, or the pulse repetition period for the s.p.e. experiment.

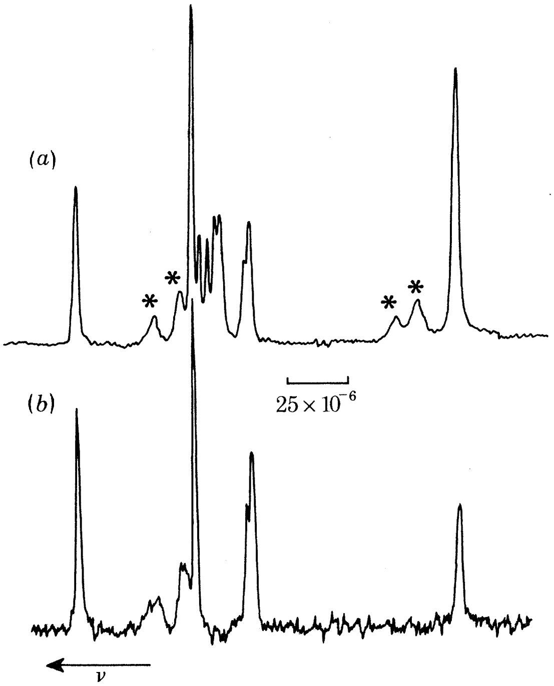


FIGURE 2. ^{13}C spectra of solid bis(isopropylamino)anthraquinone (**1**): (*a*) normal; (*b*) with the non-quaternary suppression procedure with a pre-acquisition delay. The peak at the extreme right, due to the methyl carbons, is attenuated but not suppressed. The most intense peak has contributions from both quaternary and non-quaternary carbons. The split peaks arising from carbons bonded to nitrogen (see §4*d*) are indicated by asterisks. The spectrometer operating conditions are: contact time 10 ms; 35000 transients; flip-back; recycle time 1.5 s.

3. INSTRUMENTAL DETAILS

The spectra described in this paper were obtained with a double-resonance spectrometer that is a combination of commercially available items with others designed and constructed in our own laboratory. The magnetic field is provided by a Bruker BE-38 high-resolution electromagnet having a 1 in (2.5 cm) air gap. This provides a field corresponding to proton and ^{13}C resonances at 90 and 22.6 MHz respectively. The sources for high- and low-frequency channels and for the external, pulsed proton field–frequency lock are provided by two Fluke synthesizers (models 6160A and 6160B) and a home-built oscillator, all of which are phase-locked to the reference of one of the synthesizers. Each of the two transmitter channels comprises a Bruker four-channel, broad-band, gating–phase-shifting unit and a Bruker B-KR300z-30 power amplifier. These amplifiers have a tuned final output stage with a nominal maximum output of 1 kW; they have been modified to allow computer control of the output power levels. The high-frequency receiver is a home-built, single-channel, broad-band system used mainly for tuning purposes. The low-frequency receiver was specially designed and built in our laboratory for the type of experiments described in this paper. It has an upper cut-off frequency of around 50 MHz and its gain falls off by more than 170 dB between 50 and 70 MHz. It also incorporates a particularly high rejection of 90 MHz signals and a substantial insensitivity to overload at this frequency. Quadrature phase-sensitive detection is employed, this being followed by further amplification and filtering with a dual-channel, six-pole Bessel function filter, also designed and built in our laboratory. The two channels of the latter were carefully matched in gain–frequency–phase characteristics. The preamplifiers used on both high- and low-frequency channels are broad-band, low-noise types designed and built in our laboratory. That used on the low-frequency channel incorporates a notch filter at 90 MHz to assist in the rejection of the high frequency.

The sample probe utilizes a single-coil, double-tuned circuit of the type described by Stoll *et al.* (1977), the connections to the high- and low-frequency transmitter–receiver systems being via modified Lowe–Tarr circuits (Lowe & Tarr 1968). A home-built high-pass filter is placed on the high-frequency transmitter output to eliminate interference on the low-frequency channel arising from noise in the high-frequency transmitter system. In addition, a low-pass filter (Drake TV5200-LP) placed between the probe circuit and the low-frequency preamplifier substantially enhances the isolation of the two channels with negligible loss of signal. The variable capacitors used for tuning the probe circuit were designed and built in our laboratory to satisfy the conflicting requirements of small size (to fit within the magnet air gap) and high-voltage, high-current characteristics. They were constructed by using brass or copper, with fused quartz as the dielectric. Care was needed in the selection of other components, such as the impedance-matching capacitors and the $\frac{1}{4}\lambda$ cable used to isolate low- and high-frequency channels. In the latter case the use of a PTFE dielectric cable has proved advantageous as considerable heating can occur during the long dipolar-decoupling pulses, and this can lead to softening or even melting of the polyethene dielectric used in standard coaxial cable.

Samples for measurement under m.a.r. conditions were approximately 70–100 μl in volume contained in cylindrical glass or MACOR rotors (5 mm diameter) and were used in the m.a.r. device described elsewhere (Balimann *et al.* 1980). Static samples were contained in 10 mm outside diam., thin-walled, flat-bottomed glass tubes with sample volumes of approximately 0.7 cm^3. All measurements reported here were taken at room temperature and involved matched ^{1}H and ^{13}C r.f. magnetic field strengths of *ca.* 40 kHz.

The spectrometer is controlled by a Nicolet Instruments NIC-1180 computer having 24 K of memory and a back-up disk storage system (Diablo, series 30). Pulse programming is via a NIC293A pulse programmer interfaced to the Bruker pulse modulators by a home-built decoder which, among other things, expands the capabilities of the NIC293A. The commercial device was limited by having only seven output lines; our modifications provide 15 such lines. The spectrometer is operated through a Hewlett–Packard 2645A data station, and output is onto a fast printer or graph plotter. The system has a comprehensive software package written in our laboratory, providing foreground–background operation based on the priority interrupt capability of the NIC-1180 system. Among other features the software system has a pulse programme editor–assembler which allows the writing of pulse programs in a high-level language related to the spectrometer operation. This makes the implementation of new pulse sequences straightforward and efficient. Additionally, experiments may be placed in an acquisition queue and will run sequentially under computer control.

To select the most advantageous conditions for the cross-polarization experiments it is useful to have some knowledge of the proton T_1 and $T_{1\rho}$ characteristics of the sample, since these can vary considerably and influence the choice of experimental parameters such as recycle time. In the work presented here such measurements were carried out on low-resolution pulse spectrometers operating at either 47 or 60 MHz. $T_{1\rho}$ values were measured with B_1 field strengths of between 1 and 2 mT by using the usual spin-locking sequence, while T_1's were obtained either by a 180–τ–90 sequence or, for long values of T_1, by a saturation sequence, $-(90-\tau')_n-\tau-90-$, where $T_2 < \tau' \ll T_1$.

All ^{13}C experiments were carried out by using spin temperature inversion (Stejskal & Schaefer 1975) and data routing procedures (Stejskal & Schaefer 1974*a*) designed to eliminate artefacts and effects of imperfections (Schaefer & Stejskal 1974*b*).

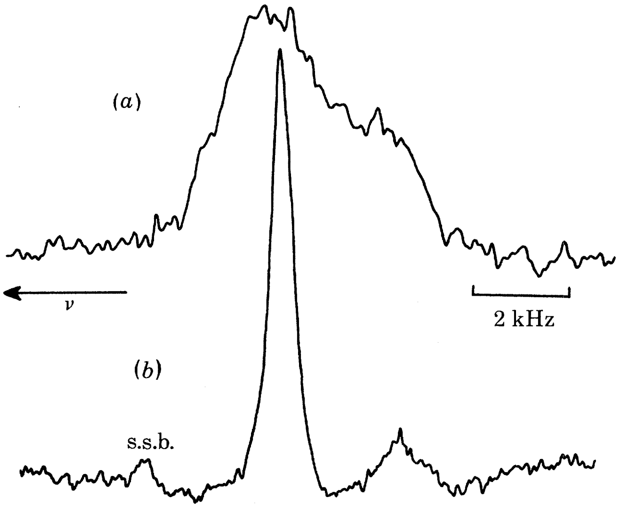


FIGURE 3. ^{13}C spectra of a coal residue (after extraction with toluene at high temperature and pressure): (*a*) static; (*b*) with m.a.r. For (*b*) the aromatic and aliphatic regions are apparent. The spectrometer operating conditions are: (*a*) contact time 1 ms; 4000 transients; recycle time 500 ms; (*b*) contact time 700 μs; 33000 transients; flip-back; recycle time 500 ms. In (*b*) a spinning sideband is indicated (s.s.b.).

4. RESULTS AND DISCUSSION

(*a*) *Insoluble materials*

The most obvious area of application of the techniques described above is to insoluble or sparingly soluble substances for which solution-state n.m.r. is impossible. Simple structural information may then be accessible via solid state n.m.r. Two types of system have dominated work reported to date, namely coal (or coal derivatives) and polymers (particularly of the cross-linked type). For coal, with its extremely complex structure, solid state n.m.r. can at least provide a semi-quantitative estimate of the proportions of aromatic and aliphatic carbon. Figure 3 shows a typical ^{13}C spectrum, obtained in our laboratory, of a coal residue, after high-temperature high-pressure solvent extraction. It may be seen that the band areas indicate that the carbon present is approximately 85–90 % aromatic. To obtain accurate data it is necessary to vary the contact time of the cross-polarization experiment and to consider closely the degree of homogeneity in the sample, particularly with respect to the presence of small amounts of paramagnetics, and the related question of spin diffusion. Figure 4 shows the spectrum of an insoluble cross-linked epoxide based on the bis-phenol A diglycidyl ether (BADGE) molecule

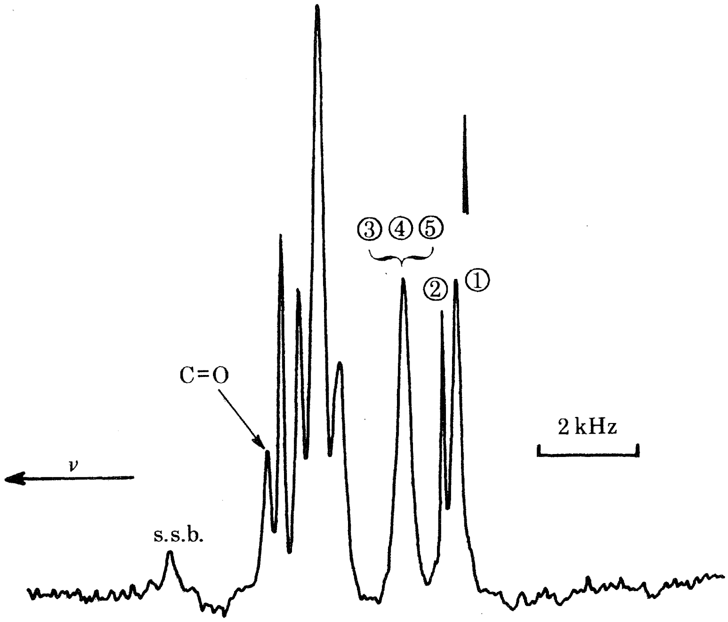
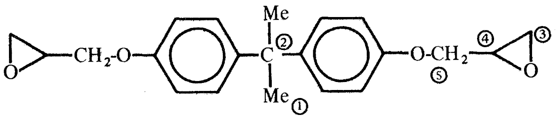


FIGURE 4. ^{13}C spectrum, with m.a.r., of an insoluble polymer prepared by cross-linking BADGE (**2**) with phthalic anhydride. The assignments of peaks in the aliphatic region are indicated (see **2**). The superimposed peak is due to liquid cyclohexane, used as a reference. A spinning sideband is indicated (s.s.b.). The spectrometer operating conditions are: contact time 1 ms; 6000 transients; recycle time 0.5 s.

(**2**) cross-linked with phthalic anhydride. Since the cross-linker contains only aromatic or carboxyl carbons, the aliphatic region in the spectrum is entirely due to the BADGE residue and assignments can be made as indicated (cross-linking opens out the epoxide group to form



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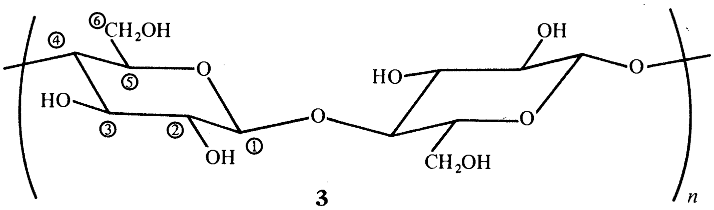
—O—CH$_2$—CH(OR)—CH$_2$—O—CO—, where the carbonyl group originates from the phthalic anhydride and R may be either H or another phthalic anhydride residue). Garroway *et al.* (1978) have made extensive studies of such spectra, including the use of relaxation measurements to investigate molecular motion in these materials.

Insoluble systems are, of course, extremely widespread and some of the spectra discussed in later sections of this article are of such materials. One more example at this point will suffice: figure 5 shows the spectrum of a plain white paper. The peaks can be readily correlated with those of the purified cellulose polymorphs (see **3**) discussed by Atalla *et al.* (1980). The sample for figure 5 was obtained by cutting *ca.* 70 disks of the paper with a cork-borer, and pressing these into our standard glass rotor with end-caps.



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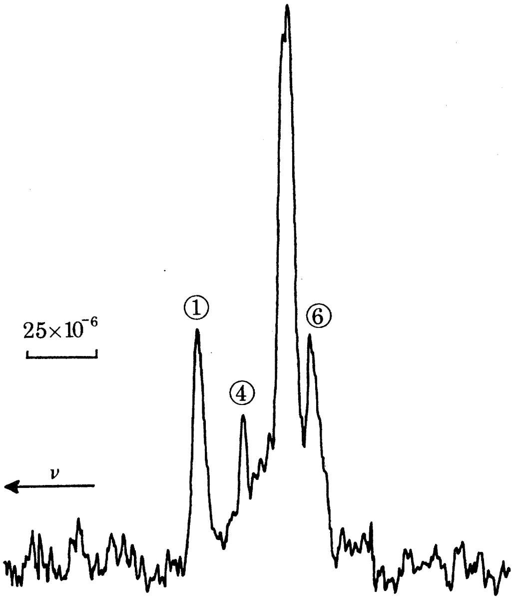


Figure 5. ^{13}C spectrum, with m.a.r., of a paper. The peak assignments are given in relation to structure **3** Conditions: contact time 4.5 ms; 30000 transients; flip-back; recycle time 1 s.

(*b*) *Effects of local environment*

(i) *Crystallographic effects*

N.m.r. spectroscopy now needs to be concerned with crystallographic matters, and a joint approach to solid state problems by X-ray crystallographers and n.m.r. spectroscopists becomes powerful. N.m.r. studies on powders can give some crystallographic information rather quickly, while work on single crystals can give much more detailed data. On the other hand, full X-ray tudies can greatly assist in understanding n.m.r. spectra of powders and in interpreting variations in shielding. Figure 6 shows the expanded-scale ^{13}C spectrum for the carboxyl region of powdered anhydrous calcium acetate. Clearly four peaks are present, probably indicating hat there are four non-congruent molecules in the unit cell. We have, however, been unable to ocate any published (detailed) X-ray studies of this material and this deduction remains to be onfirmed. Interestingly, the methyl resonance is a single line, indicating a spatial dependence f these effects. Spectra of potassium acetate, on the other hand, show no splitting of either the arboxyl or the methyl region under our available resolution. The existence of such effects must e clearly realized when n.m.r. spectra of polycrystalline materials are being examined.

The existence of non-congruent molecules in unit cells is relatively uncommon, but we have observed several other instances where this appears to be the case. Figure 7 shows the spectrum of 2,4-dinitrotoluene, which clearly shows a splitting of 65 Hz for the methyl peak, thus suggesting there are two non-congruent molecules in the unit cell. Subsequent X-ray work (M. J. Begley, unpublished, 1980) has shown this to be so (the space group is $P2_1/c$), and it appears to be the first system where such n.m.r. evidence has preceded the X-ray information (though an old and somewhat ambiguous X-ray report (McCrone & Tsang 1954) is in existence.) The aromatic region of the n.m.r. spectrum, although it is not straightforward to interpret, does not appear to give any simple doubling of peaks, so the variations in local environment would appear to be largest for the methyl groups.

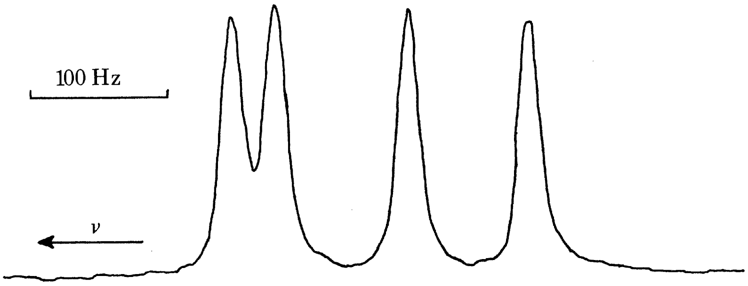


FIGURE 6. Expanded-scale ^{13}C spectrum of anhydrous calcium acetate powder (carboxyl region only) obtained with m.a.r. The peaks are at 187.1, 185.7, 181.5 and 177.7 × 10^{-6} from the signal due to tetramethylsilane (external referencing procedure). Conditions: contact time 10 ms; 30000 transients; flip-back; recycle time 1.5 s.

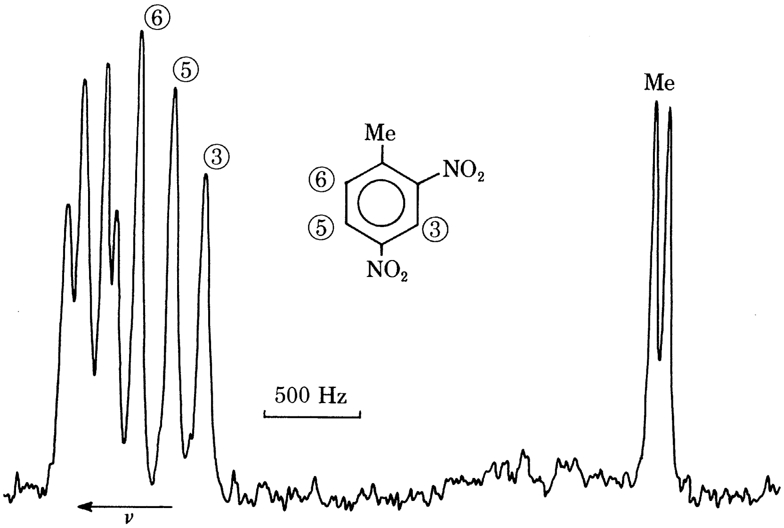


FIGURE 7. ^{13}C spectrum of 2,4-dinitrotoluene. Assignments are given except for the quaternary carbons. Peaks marked 3, 5 and 6 are at δ_C = 121, 128 and 135 × 10^{-6} respectively. Conditions: contact time 10 ms; 12000 transients; flip-back; recycle time 3 s.

Such non-congruence between different molecules also has its intramolecular counterpart, since it cannot be assumed that n.m.r. equivalence of two groups within a molecule in the solution state will continue in the solid. Striking examples of this have been reported by Hill *et al.* (1979) who have shown that the carbonyl and α-carbon atoms of optically pure solid tartaric acid diastereomers give split ^{13}C n.m.r. peaks because of the lack of symmetry within a single acid molecule in the crystals.

(ii) *Chemical shift variations*

There is no *a priori* reason to expect isotropic average chemical shifts in solids to be the same as those for the corresponding solutions, since 'medium' effects are likely to be strong. The results of non-congruency discussed above provide an example of this; for the carboxyl carbon of calcium acetate (figure 6) the range of shifts in the solid is 9.4×10^{-6}. Clearly, then, the shifts obtained for powders are not necessarily molecular parameters. Haeberlen (1978) has vividly illustrated this point with reference to the proton n.m.r. of pyromellitic acid dianhydride and of calcium and lead formates, using shielding tensor components rather than their averages. In the case of the formates he has shown that simple corrections to take account of intermolecular effects give consistent results.

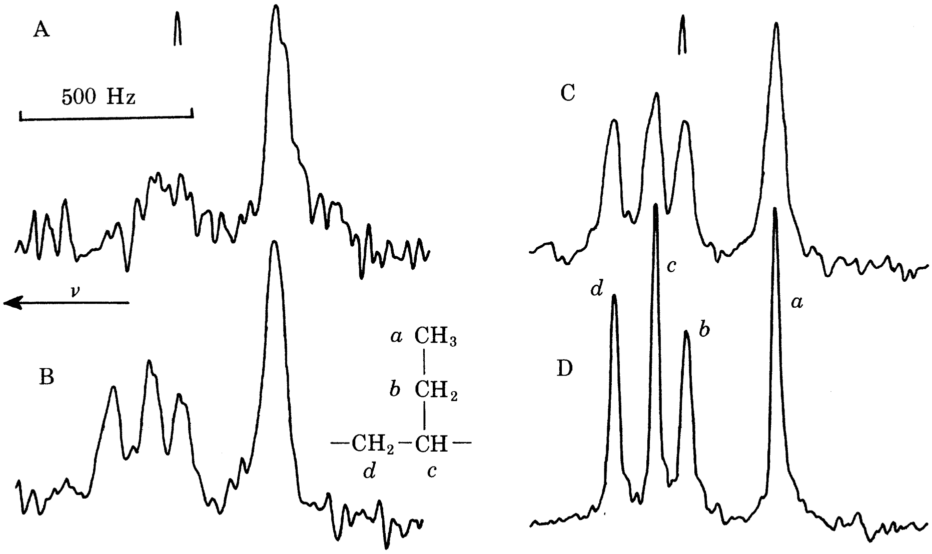


FIGURE 8. ^{13}C spectrum of isotactic polybutene, obtained at ambient probe temperature after heating to 130 °C to convert the sample to the type II (11:3) polymorph. The spectra were obtained at different times after conversion: A, immediately; B, 20 h; C, 2 days; D, 13 days. Spectra A and B have amplification factors × 4 and × 2.5, respectively, relative to spectra C and D. The peak assignments are indicated on D. Conditions: contact time 1 ms; 4000 transients; recycle time 1 s. The peaks superimposed above A and C are from liquid cyclohexane, used as a reference.

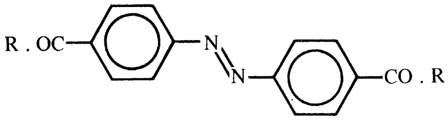
Because of uncertainties in referencing procedures (particularly with regard to bulk susceptibility effects), the clearest indications of chemical shift changes with phase comes from consideration of intramolecular shift differences. Thus for isotactic polybutene (figure 8D) these are as shown in table 1.

TABLE 1

shift difference ...	$d-c$	$c-b$	$b-a$
solution	5.2	7.5	17.1×10^{-6}
solid	6.9	4.8	14.5×10^{-6}

Qualitatively it can be seen that for the solid peak *c* is nearer to *b* than to *d*, whereas the reverse is true in solution. Similar effects have been reported for polypropene (Balimann *et al.*

1980). Such variations are not, of course, confined to polymers, but occur also for simpler molecular systems. We have found, for instance, that for the *trans*-diazobenzene derivatives



4

(**4**; R = OH, Cl) the carbonyl carbon resonates *ca.* 8 × 10^{-6} to higher frequency in the solid than in solution in dimethyl sulphoxide. This could be explained by hydrogen-bonding in R=OH, but not for R=Cl, for which the shift change is nearly as big.

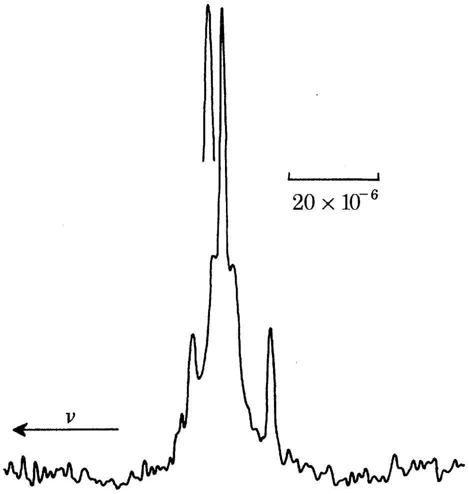


FIGURE 9. ^{13}C spectrum of a rubbery ethene–propene copolymer, obtained under s.p.e. conditions: (90° pulses; 15000 transients; recycle time 300 ms). The superimposed peak is that from polyethene (dominantly the 'crystalline' component) obtained by using cross-polarization (contact time 1 ms; 2000 transients; flip-back; recycle time 1 s).

Shift changes may also be observed between different physical states of the same system. Thus Fyfe *et al.* (1979) and Earl & VanderHart (1979) have shown that 'amorphous' polyethene gives a signal 2.4 × 10^{-6} to low frequency of that for 'crystalline' polyethene, spectral discrimination being readily achieved by using s.p.e. methods with rapid pulse repetition to enhance the peak due to the 'amorphous' component, which has a substantially shorter T_1 (^{13}C) than the 'crystalline' component. We have found similar effects in comparing spectra from a rubbery copolymer of ethene and propene, obtained with the s.p.e. sequence, with that of crystalline polyethene (figure 9). The copolymer may be envisaged as a polyethene system with random methyl side chains.

(iii) *Line width variations*

Since chemical shifts can vary with the crystallographic site, as is true of the carboxyl groups of figure 6, lack of sufficient resolution can lead to apparent line broadening. Indeed, we presume that this occurs for the methyl carbon resonance of anhydrous calcium acetate, for which we only observe a single line (though its width is, within experimental error, equal to that of each carbonyl carbon line). Effects of this type become most important for amorphous systems. In such cases a great range of local environments can exist for a given carbon, leading to a distribution of chemical shifts and therefore to line broadening. Glassy polymers, for example, yield carbon resonances that are typically *ca.* 60 Hz broad at half-height. However, not all carbons in the system will be affected similarly. Those on the periphery of a molecule will be most affected by intermolecular heterogeneity, whereas carbons that are not near the periphery will be little affected. In particular, quaternary carbons will be physically shielded from neighbouring molecules and therefore may be expected to yield sharp lines. This is clearly illustrated in figure 4; peak 2 (see **2**) is substantially sharper (less than 25 Hz in width) than the others.

Such variations in line width also show up for 'crystalline' polymers, such as isotatic polypropene and polybutene (see figure 8). In these cases the structure involves a 3:1 helix (three polymer units to a complete turn of the helix), thus causing a non-equivalence of carbon atoms of the same chemical type. For polybutene, higher-field experiments (Gray & Hill 1980) show splittings in the spectra, though the origin of these splittings has not been discussed in detail. Splittings are also seen for small molecular mass polymers of BADGE in the crystalline state (Ritchey *et al.* 1979) and it is clear that such effects lead directly to the larger line widths in polymers of higher molecular mass (or of related copolymers, as for the cross-linked epoxides). Sometimes splittings and/or line broadening may be caused by the effects of asymmetry, as in the case of tartaric acid derivatives (Hill *et al.* 1979) mentioned above.

(*c*) *Chemical effects*

There are many ways in which molecular structure in the solid state can differ from that in solution. We choose to illustrate three areas (tautomerism, polymorphism and hindered intramolecular motion) that we believe to be of general interest and widespread occurrence.

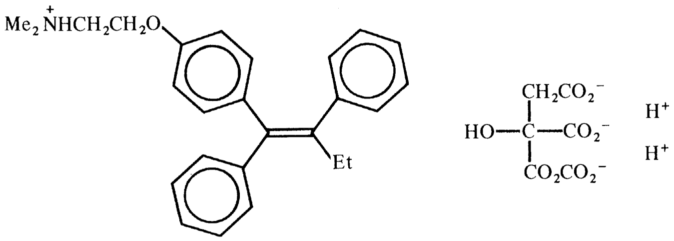
(i) *Tautomerism*

One of the most important types of tautomerism is that between keto and enol forms. The results of solution-state work do not necessarily have any bearing on the question of deciding the tautomeric form of a solid. Of course, other forms of spectroscopy may be used in such a case, but we felt that ^{13}C n.m.r. is likely to provide a clear distinction. Figure 10 shows the solid state ^{13}C spectrum of a compound known to exist in both forms. There is no peak higher in frequency than $\delta_C = 169.0 \times 10^{-6}$. Spectra in solution in acetonitrile (where both keto and enol forms exist in equilibrium) show that the carboxyl carbon of the keto form resonates at $\delta_C = 195.7 \times 10^{-6}$. It is therefore clear that the solid examined is in the enol form. In confirmation of this statement, the peak at $\delta_C = 101.5 \times 10^{-6}$, marked with an asterisk in figure 10, may be assigned to the enolic carbon ($\delta_C = 104.0$ in CD_3CN), and the only peak in the region $\delta_C = 20\text{–}40 \times 10^{-6}$ in the solid is at $\delta_C = 27.5 \times 10^{-6}$, whereas for a solution in CD_3CN there are peaks at $\delta_C = 27.4 \times 10^{-6}$ (enol) and $\delta_C = 33.7 \times 10^{-6}$ (keto).

(ii) *Polymorphism*

By its very nature, polymorphism must be investigated by solid state methods. The phenomenon is of considerable importance in several areas of the chemical industry. X-ray diffraction studies are time-consuming and not always feasible. For many problems a full crystal structure determination is not necessary and high-resolution ^{13}C n.m.r. can offer rapid information. Examples from cellulose chemistry have already been published (Atalla *et al.* 1980).

We have investigated two such situations from different branches of the chemical industry. The first concerns a citrate of chemical structure **5**. This material exists in two polymorphic forms whose ^{13}C spectra are shown in figure 11. There are clear differences between the spectra, showing that ^{13}C n.m.r. can be used for monitoring the polymorphism. It is of interest to note that the carboxyl carbons of the citrate ion give rise to three separate peaks ($\delta_C > 160 \times 10^{-6}$) for both polymorphs. The distinction between the two $CH_2CO_2^-$ carboxyl peaks is clearly greater for form B than for form A (in solution these two carboxyl carbons are equivalent). On the other hand, the peaks marked with an asterisk, arising from the quaternary carbon of the citrate ion, are at the same chemical shift ($\delta_C = 75.5 \times 10^{-6}$, compared with 72.0×10^{-6} for a solution in dimethyl sulphoxide). It should prove possible to relate these facts to the crystal structures, and it is likely that differences in the orientation of aromatic rings and in the extent of hydrogen bonding will be the most powerful influences. We are attempting such rationalization, since the crystal structure of form B is known.



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Our second example of polymorphism is that of polybutene. When the type I polymorph (figure 8D) is heated to *ca.* 130 °C for about 15 min, it is converted to a form (type II) that has an 11:3 helical structure (Turner-Jones 1963). Rapid cooling to ambient temperature renders this form sufficiently stable for a spectrum to be obtained, illustrated in figure 8A. This spectrum is substantially different from that of the type I form (figure 8D), taken under similar conditions. (Values of T_1(H) and $T_{1\rho}$(H) for the two forms differ substantially, and the spectometer operating conditions for figure 8 are optimized for the type I form.) The type II spectrum appears to show broader lines, presumably resulting from the greater range of chemical shifts expected from an 11:3 helix (probably together with motional differences from the type I form). At room temperature the type II polymorph reverts to the type I form over a matter of days, and the differences in the spectra of the two forms are sufficiently marked for the change to be readily monitored (and its rate measured) by ^{13}C n.m.r.: see figure 8.

(iii) *Hindered intramolecular motion*

Processes such as internal rotation and ring inversion are expected to occur much more slowly in the solid state than in solution at the same temperature, a given rotamer or invomer being 'frozen' in for the solid. Internal rotation about single C–C bonds is normally rapid on the n.m.r. timescale at ambient temperature for solutions, but there is considerable evidence that this is not so for solids. For instance, figure 12 shows the aromatic region of the ^{13}C spectrum of the solid dyestuff **6**. The bands on the left are due to the quaternary carbons, leaving eight peaks for the CH carbons, implying that none of them are equivalent. In solution only four peaks are seen for the CH carbons. It is not yet possible to assign unequivocally the peaks in figure 12 but table 2 gives some suggestions by comparing the solution ($CDCl_3$) and solid data. The peak due to the cyanide carbon occurs in the same region ($\delta_C = 117.7 \times 10^{-6}$ for a solution) and has been identified ($\delta_C = 121.5 \times 10^{-6}$) for the solid state spectrum by an n.q.s. experiment; the effect of the change of phase on the chemical shift is therefore substantial. The additional splittings shown in the solid spectrum as listed in table 2 arise from a mixture of intramolecular and intermolecular effects. In many cases the former will predominate, as can be reasonably

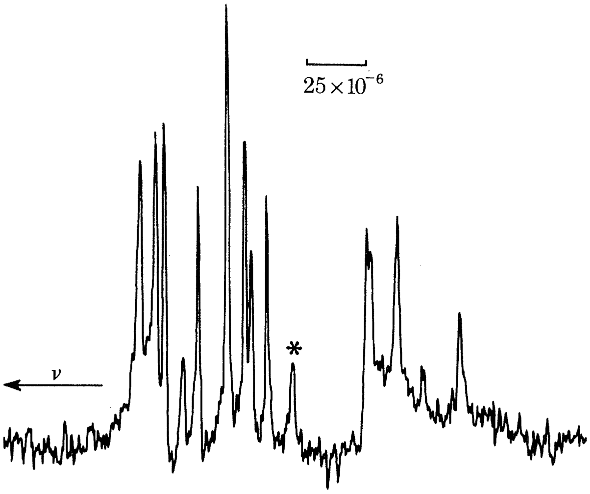


FIGURE 10. ^{13}C spectrum of a compound capable of keto–enol tautomerism. Conditions: contact time 4 ms; 45000 transients; flip-back; recycle time 1 s.

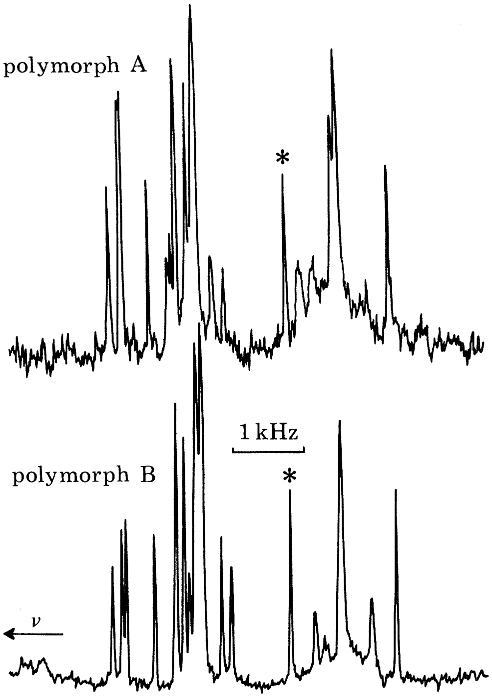
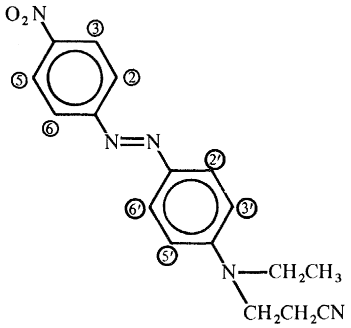


FIGURE 11. ^{13}C spectra of two polymorphs of structure 5. Conditions: polymorph A: contact time 5 ms; 40000 transients; recycle time 2 s; polymorph B: contact time 10 ms; 45000 transients; recycle time 1 s. Both spectra were recorded by using a flip-back sequence. The peaks marked with asterisks are discussed in the text.

concluded if the average shifts are close to those observed for the solution state, and it should be feasible in the medium term to extract conformational information and/or data on anisotropies in magnetic susceptibilities of chemical groups (such as the diazo group). If intermolecular effects can be neglected, the magnitudes of the splittings given above show that the diazo group confers a shift difference of *ca.* 18×10^{-6} on the *ortho* positions and *ca.* 3×10^{-6} on the *meta* carbons, whereas the β-cyanoethylethylamino group causes a relatively small *ortho* effect, as expected.



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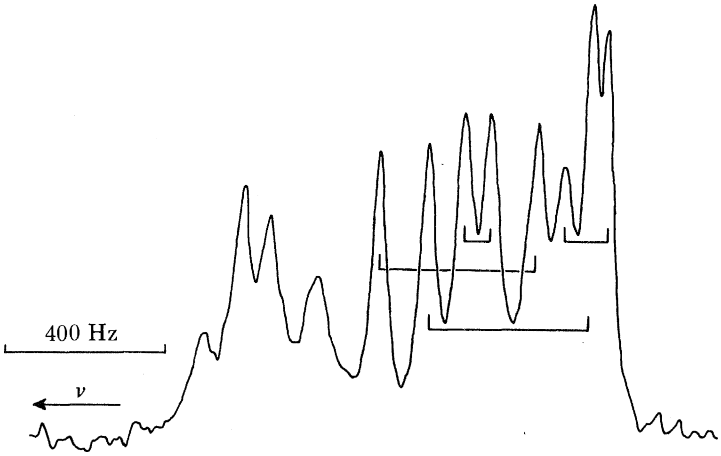


FIGURE 12. ^{13}C spectrum of a diazo compound (**6**), aromatic region only, with a suggested pairing of peaks (see the text). The high-frequency peaks are due to the quaternary carbons. Conditions: contact time 5 ms; 80000 transients; flip-back; recycle time 750 ms.

TABLE 2

carbons	2′,6′	3′,5′	2,6	3,5
$10^6\ \delta_0$				
solid	134.2, 116.4	113.7, 108.5	129.2, 110.2	125.2, 122.3
solid (splitting)	17.8	5.2	19.0	2.9
solid (av.)	125.3	111.1	119.7	123.8
solution	126.4	111.9	122.9	124.7

(*d*) *Coupling to heteronuclei*

Spin–spin coupling interactions are of two types, scalar and dipolar. For liquids, molecular tumbling averages the latter to zero and the former to their isotropic values (tensor traces). Isotropic scalar coupling constants have given much information of chemical importance, and it might be hoped that similar data could be obtained for solids. In the ^{13}C–^{1}H cross-polarization experiment, coupling between carbons and protons of both scalar and dipolar origin is eliminated from the spectra. Magic angle rotation (at accessible rates) will average weak dipolar coupling to spin-$\frac{1}{2}$ nuclei other than protons, but may have a more complex effect on such interactions with quadrupolar nuclei (see below). Scalar coupling to all nuclei should be averaged to the isotropic values by m.a.r., except in rare circumstances (Andrew & Farnell 1968).

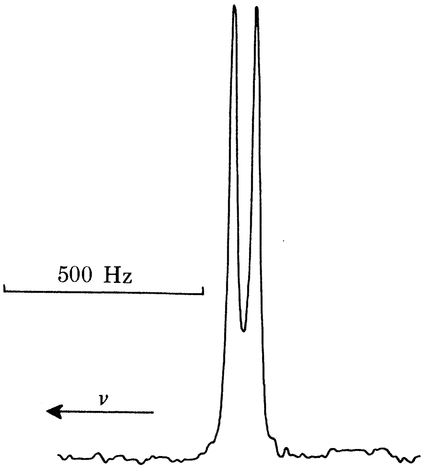
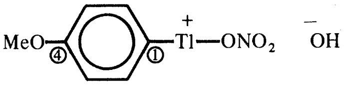


FIGURE 13. ^{13}C spectrum of trimethylphosphine sulphide. Conditions: contact time 10 ms; 4000 transients; recycle time 1 s.

(i) *Scalar coupling to spin-$\frac{1}{2}$ nuclei*

If high-abundance spin-$\frac{1}{2}$ nuclei other than ^{1}H (^{19}F, ^{31}P, etc.) are present in solids, coupling will influence the c.p. m.a.r. spectrum. For ^{19}F, problems may arise from strong (^{19}F, ^{13}C) dipolar interactions, but for (^{31}P, ^{13}C), coupling m.a.r. at modest speeds suffices to remove these effects, and splittings due to scalar coupling may be revealed. For instance, the spectrum of solid Me_3PS shows a clean doublet (figure 13) with $|J_{PC}| = 54$ Hz, close to the solution-state value (56.1 Hz, McFarlane 1968).

Figure 14 shows another example, in this case involving thallium, which has two spin-$\frac{1}{2}$ isotopes, ^{203}Tl (29.5%) and ^{205}Tl (70.5%) with similar n.m.r. properties. The compound studied (**7**) is insoluble (the precise nature of the bonding is not known) but the structure shown



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is thought to be the most probable. The spectrum shows nine lines, and the non-quaternary suppression experiment enables those due to C^1 and C^4 to be assigned, giving $|^{1}J_{TlC}| = 5215 \pm 5$ Hz and $|^{4}J_{TlC}| = 97 \pm 5$ Hz. Chemical shift considerations allow the assignment of the methyl peak but ambiguities remain for the other lines. Interestingly, the analysis does not require considerations of non-equivalence for C^2 and C^6 (or of C^3 and C^5).

(ii) *The influence of* ^{14}N

It might be expected that spectra of molecules containing quadrupolar nuclei would show some special features, because quadrupolar interactions with intramolecular field gradients will not be effectively averaged by molecular tumbling as they are for solutions. This indeed proves to be so, as may be particularly noted for systems containing nitrogen. Carbon atoms directly bonded to ^{14}N do not, as a rule, give rise to sharp single peaks in ^{13}C solid state n.m.r. under m.a.r. conditions. This is not due to (^{14}N,^{13}C) scalar coupling, since values of $^{1}J_{\mathrm{NC}}$ are known to be in general small, and the observed spectra are not triplets. It is, in fact, common to see unsymmetrical broadened doublets, as illustrated in figure 15. The splittings may be substantial (e.g. 119 Hz and 108 Hz at 22.6 MHz for 1,4-dinitrobenzene and 2,6-dinitrotoluene respectively), but in other cases, such as amino acids (Groombridge *et al.* 1980) they are smaller, and they may be impossible to resolve, as is presumably true for tetraethylammonium bromide (Groombridge *et al.* 1980), for which only a single, rather broad line is observed. In addition, if the ^{14}N spins are undergoing sufficiently rapid transitions (for their own axes of quantization) due to spin–lattice relaxation, this may effectively decouple them from the ^{13}C spins, and no

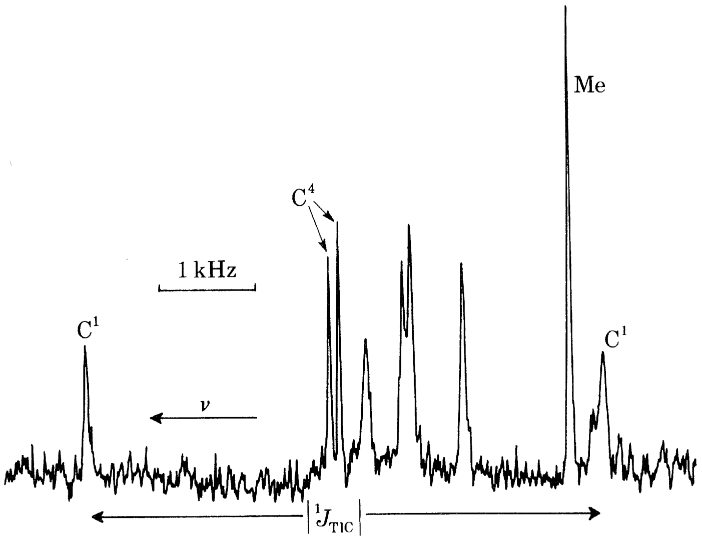

FIGURE 14. ^{13}C spectrum of the thallium compound **7**. Conditions: contact time 10 ms; 10000 transients; flip-back; recycle time 2 s.

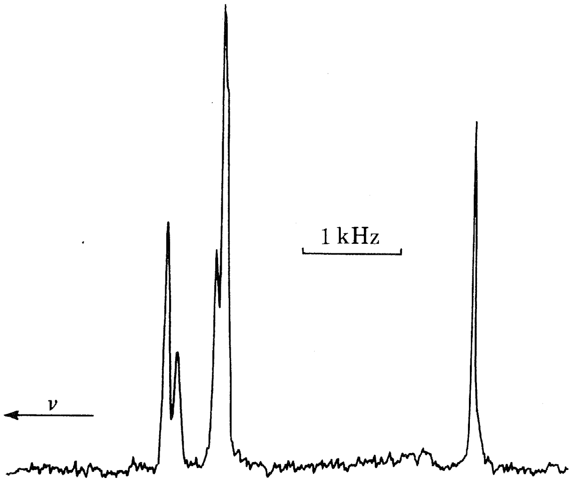

FIGURE 15. ^{13}C spectrum of 2,6-dinitrotoluene. The highest frequency pair of lines is due to the 2 and 6 carbons. Conditions: contact time 5 ms; 10000 transients; flip-back; recycle time 5 s.

effect will be observed in the ^{13}C spectrum. This is probably so for the diazobenzenes (see table 3). The influence of ^{14}N is apparent in figures 2, 7, 11 and 12 as well as figure 15.

The effects are due to the competing influences of the static field, B_0, and the electric field gradient, q, on the ^{14}N nuclear spin. Magic angle rotation cannot then fully average the (N,C) dipolar interaction. For a powder all angles between B_0 and q are allowed, and the observed effect is an average. Kundla & Alla (1979) have shown that doublet splittings can be explained.

TABLE 3. BAND SHAPES FOR CARBON BONDED TO ^{14}N

(Splittings quoted are for 22.63 MHz.)

chemical type	examples	band shapes
primary ammonium salt, CNH_3^+	glycine, valine, alanine, hexamethylenediamine dihydrochloride	doublet (splitting *ca.* 100 Hz)
quaternary ammonium salt, C_4N^+	tetraethylammonium bromide	broad single line (width *ca.* 80 Hz)
nitroaromatic	*p*-nitrotoluene, *p*-dinitrobenzene dinitrotoluenes	clear doublet (splitting *ca.* 110 Hz; figure 15)
diazobenzenes	4,4′-disubstituted diazobenzenes, compound **6**	no splitting seen
secondary amine	compound **1**	clear doublet splittings 200 and 260 Hz (figure 2)

The splittings are a function of the ratio of the ^{14}N Zeeman and quadrupolar energies, and should vanish in the high-field limit, i.e. they should decrease as B_0 increases. They will also depend on q and are thus expected to show some correlation with the chemical environment of the nitrogen. We are principally interested in the diagnostic possibilities of the ^{13}C band shapes for carbons bonded to ^{14}N and for their use in spectral assignment. Table 3 summarizes some of our observations. Comparison of figures 2 and 15 shows that the asymmetry of the splitting due to the ^{14}N is in an opposite sense for a nitro group and an amino group. We suggest that this is related to the different orientation of the ^{13}C–^{14}N internuclear vector in the principal axis system of the ^{14}N quadrupole interaction in these two chemically different situations. Again, this may be used diagnostically.

Since the magnitude of the splitting depends on the (N,C) dipolar interaction, it varies with the inverse cubic power of the (N,C) distance, r_{NC}. Thus the effect is expected to be only of importance for carbon atoms directly bonded to nitrogen. For a given nitrogen the splitting of neighbouring carbons may vary. This seems to be the case for bis(isopropylamino)anthraquinone (figure 2), for which the splitting of the aliphatic carbon (200 ± 5 Hz) is substantially less than that of the aromatic carbon (260 ± 5 Hz). In principle this gives geometry information, but asymmetry in the electric field gradient complicates further evaluation.

Similar effects may occur for other quadrupolar nuclei (^{2}H is a particularly interesting case that has not yet been properly investigated). We have examined several chlorine-containing compounds. These do not seem to give noticeably broadened lines, probably because the quadrupole moments of ^{35}Cl and ^{37}Cl are higher than tht of ^{14}N and electric field gradients are also usually higher, thus substantially shortening T_1. However, there is one report (Lyerla 1979) of broadening effects attributed to dipolar interactions between carbon and chlorine.

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Corporate Laboratory). We have many people to thank for gifts of samples and for useful discussions, including A. M. Chippendale and A. Mathias (I.C.I. Organics Division) A. Bunn and M. E. A. Cudby (I.C.I. Plastics Division), J. K. Becconsall and P. Loftus (I.C.I. Corporate Laboratory), G. Bedford (I.C.I. Pharmaceuticals Division), B. P. Stark (Ciba–Geigy U.K. Ltd), P. Belton and E. Smith (Unilever Research), W. R. Ladner and C. Snape (Coal Research Establishment, N.C.B.), R. Schmutzler (Braunschweig University) and A. McKillop (University of East Anglia). We also acknowledge invaluable help from A. G. Strike and M. J. S. Burgess in constructing the spectrometer, and from A. G. Oliver and K. H. Mikhchi in operating it. One of us (S.F.T.) thanks Unilever Research for collaborative work under a C.A.S.E. Research Studentship.

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Discussion

W. DERBYSHIRE (*Department of Physics, University of Nottingham, U.K.*). Could I ask for some clarification on the situation regarding samples of low proton content, such as the coals? To be specific, how low a proton concentration can be tolerated? In addition, as a non-uniform proton distribution could occur within the sample, how sure can we be that all the carbon is being sampled?

R. K. Harris. These questions are of considerable practical importance but have so far not received adequate attention in the literature. Some very careful studies are required, with the use of a variety of conditions (variable cross-polarization contact times, for example). The non-quaternary suppression experiment might give valuable additional information. The existence of small amounts of paramagnetic material, particularly if non-uniformly distributed, probably causes further complications. I believe that Professor Gerstein has some detailed information on these points.

B. C. Gerstein. In a paper which is in press in *Fuel, Lond.*, we report that in a number of coals that we have investigated, there is not a uniform proton $T_{1\rho}$; in particular we find two proton $T_{1\rho}$'s; one of order of 100 μs, and the other of order of 1 ms. Thus for a cross-polarization time of 3 ms, those carbon atoms depending *only* on the proton with the short rotating frame relaxation would not be efficiently cross-polarized. In addition, we have performed carbon spin counting experiments, using strong proton decoupling, and have found that the percentage of carbon seen even in these experiments ranges from 60 to 100%. The fraction of carbon seen does not correlate with the number of $S = \frac{1}{2}$ free radicals present (for $g = 2$). I suspect that the carbons not seen have either a very long (e.g. in adamantane-like structures) or a very short (e.g. carbon in large polynuclear aromatic rings containing free radicals) spin–lattice relaxation times.

J. E. Page (*Glaxo Group Research Ltd, Greenford, Middlesex, U.K.*). How much material did the authors use for measurements such as those on the polymorphic compounds?

R. K. Harris. Typically we use *ca.* 100 mg of powdered material. This quantity depends on the density of the sample, of course. The volume available for the sample in our present arrangement is *ca.* 70 mm³, though we expect to go to a system using *ca.* 240 mm³ in the near future.