groups in 1,2,3,4,5,6,7-heptamethylindene, $C_9(CH_3)_7H$, also have a large cumulative acid-weakening effect (7.0 pK_a units). In both $C_5(CH_3)_5H$ and $C_9(CH_3)_7H$ the major acid-weakening effects are believed to be due to methyl hyperconjugative stabilization in the undissociated acids and methyl steric inhibition of solvation in the anions.

The acidity data revealing a large hyperconjugative methyl effect in $C_5(CH_3)_5^-$ ions are consistent with the chemistry found in the cyclopentadienyl- and pentamethylcyclopentadienylmetal complexes. The large, additive methyl hyperconjugative effect found in $C_5(CH_3)_5H$ must also be present in $C_5(CH_3)_5$ metal complexes. This hyperconjugative effect is the source of the increased electron-donor strength of $C_5(CH_3)_5$ ligands, relative to C_5H_5 ligands. The increased donor strength of $C_5(CH_3)_5$ ligands causes an increase in the electron density in $C_5(CH_3)_5$ metal complexes, relative to C_5H_5 metal complexes. For example, as the number of CH_3 groups in polymethylated ferrocenes increases, the electron density on the metal and the tendency to undergo spontaneous oxidation in air increases.[13] In another study, when $Rh[\eta^5\text{-}X](CO)_2$ was allowed to react with n-Bu_3P, the rate was about 100 times slower for $X = C_5(CH_3)_5$, compared to $X = C_5H_5$. This rate retardation was ascribed in part to the increased electron density on Rh in the pentamethylcyclopentadienylmetal complex. However, part of this retardation is believed to have a steric origin since $(n\text{-BuO})_3P$ reacts more rapidly than n-Bu_3P despite its lower basicity.[6] In contrast, in a somewhat related study, we have found that in S_N2 reactions of $C_5(CH_3)_5^-$ and $C_5H_5^-$ ions with several alkyl halides in Me_2SO solution, the methyl groups cause little or no steric hindrance to the approach of the electrophile.[14] With the aid of a linear Brønsted plot,[15] rate comparisons can be made at the same anion basicity, effectively eliminating any electron-density differences in $C_5H_5^-$ and $C_5(CH_3)_5^-$ ions.

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Long-Range Proton–Nitrogen Spin Coupling Constants via Polarization-Enhanced Two-Dimensional ^{15}N NMR

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Most values of spin–spin coupling constants between ^{15}N and ^1H nuclei separated by two or more intervening bonds have been obtained from ^1H NMR spectra of ^{15}N-enriched compounds.[2] Such a strategy for determining long-range J_{NH} values is costly and may be synthetically impractical. Moreover there is no guarantee that ^1H NMR of enriched compounds will provide access to J_{NH} since the line widths of the pertinent proton multiplets and homonuclear couplings to other protons may obscure the coupling to ^{15}N. On the other hand, the direct evaluation and assignment of long-range J_{NH} from proton-coupled ^{15}N spectra is usually impractical because of the complexity of the spectra. In this paper we demonstrate a new two-dimensional Fourier-transform NMR method for observing and assigning ^{15}N–^1H coupling constants selectively. The technique substantially reduces the requirement for ^{15}N enrichment and at the same time eliminates the obfuscation created by line broadening and/or extraneous scalar couplings.

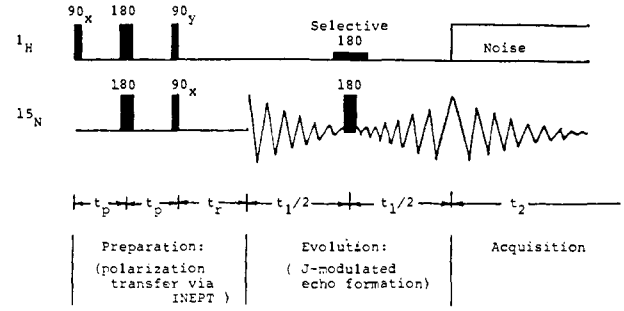

Figure 1. INEPT-enhanced, selective 2D-J pulse sequence. The pulses and delays in the preparative stage are standard for the refocused INEPT experiment[4b] with $t_p = (4J_{NH})^{-1}$ and $t_r = (2J_{NH})^{-1}$ for NH or $t_r = (4J_{NH})^{-1}$ for NH_2 and NH_3 spin systems. Here J_{NH} is the coupling between ^{15}N and the proton(s) used to effect the polarization transfer. In the evolution period, $t_1/2$ is incremented in 32 regular steps, each typically of 40-ms duration to give a spectral width of 12.5 Hz in the F_1 dimension. The selective 180° (^1H) pulse is 25 ms ($\gamma_H B_2 = 20$ Hz) and is applied at the center of the proton line of interest. If the proton of interest is coupled to nonequivalent ^{15}N spins, nonselective 180° (^1H and ^{15}N) pulses should be applied at the midpoint of the refocusing delay, t_r, to eliminate phase shifts introduced by the chemically shifted ^{15}N resonances.

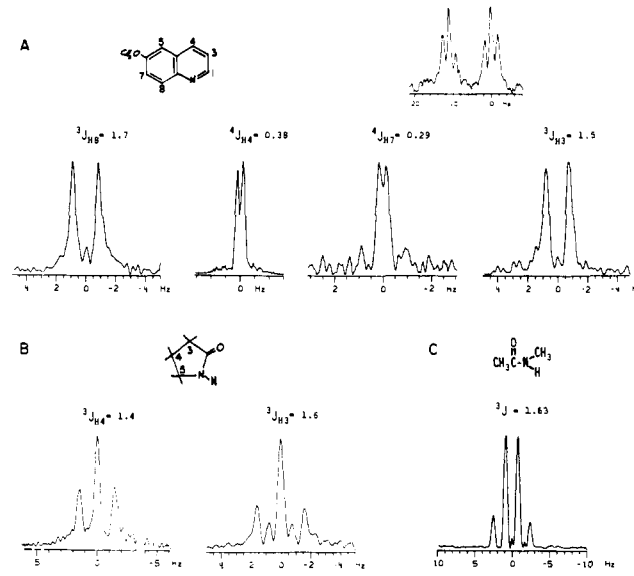

Figure 2. Long-range, natural-abundance ^{15}N–^1H coupling constants via INEPT-enhanced, selective 2D-J spectroscopy. (A) 6-Methoxyquinoline (2 M in chloroform-d_1), the chemical shifts of the selectively flipped protons were from left to right at 6.79, 7.42, 6.97, and 7.70 ppm from Me_4Si. (B) 2-Pyrrolidinone (2 M in H_2O), the chemical shifts of the $C(3)H_2$ and $C(4)H_2$ groups were at 2.92 and 2.71 ppm, respectively. (C) N-Methylacetamide (2 M in H_2O), the chemical shift of the acetyl CH_3 was at 2.55 ppm. (insert) 1-D, ^1H-coupled INEPT spectrum of (A). The coupling constants are accurate to ±0.05 Hz. The experiments were performed at 30.4 MHz by using a Nicolet-300 (wide bore) spectrometer equipped with a 293B pulse programer. Temperature was 25 °C.

The experiment is similar to the one performed in selective 2D-heteronuclear J spectroscopy[3] but with a important modification introduced in the preparative stage of the experiment (Figure 1). Namely, a *polarization–transfer* pulse sequence such as INEPT[4] is used to generate transverse ^{15}N magnetization, which is enhanced by a factor of $\gamma_{^1H}/\gamma_{^{15}N} = 10$ compared with that

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created by a single 90° (^{15}N) pulse. Since the components of ^{15}N magnetization are in an antiphase relationship, a delay t_r is introduced to allow the magnetization to come into phase.[4b] At this point the experiment proceeds as described by Bax and Freeman.[3]

Some novel examples of long-range NH couplings observed by this technique are shown in Figure 2. The spectra are projections of a portion of the two-dimensional ^{15}N FT-NMR spectra onto the F_1, i.e., J frequency, axis. Each 2D spectrum was acquired in ca. 30 min. and processed in the usual way.[3] Where comparison is possible (vide infra), the observed J values are in good agreement with similar coupling constants observed in related compounds.[2]

The advantages of combining polarization enhancement with the selective 2D-J method are seen by comparing the 3- and 4-bond J spectra of 6-methoxyquinoline with its one-dimensional, proton-coupled INEPT spectrum obtained in the same total time (ca. 2h).[5] Clearly the coupled spectrum is too poorly resolved to give any indication of the 4-bond couplings or how the observed 3-bond splittings should be assigned. By contrast, all but the 4-bond coupling between H(5) and N, which we estimate to be less than 0.1 Hz,[6] are resolved and unambiguously assigned via the 2D-J spectra. To our knowledge the J values reported here for the 3-bond (H(8),N) and 4-bond (H(5),N) and (H(7),N) pairs are the only examples of J_{NH} couplings for these particular geometries.

The values of the 3-bond coupling constants in the aliphatic systems are also of interest for they depend on the dihedral angle θ and provide calibration of the relationships between θ and $^3J_{NH}$.[7,8] In 2-pyrrolidinone the observed values for $J_{NH(3)}$ = 1.6 and $J_{NH(4)}$ = 1.4 Hz (Figure 2B) are in good agreement with calculated values (1.6 (ref 6) and 1.5 Hz (ref 7), respectively) for θ's of 120°.[9] The rotationally averaged ($^3J_{NH}$) in N-methylacetamide (1.63 Hz) also agrees well with the calculated value of 1.8 Hz.[7]

To summarize, we have demonstrated that a polarization-transfer sequence preceeding the selective 2D-J experiment markedly increases sensitivity while retaining the spectral simplicity and high resolution inherent in the 2D-J experiment.[10] Clearly the technique facilitates the observation of ^{15}N–^1H coupling constants at natural abundance (0.37%) without requiring an excessive investment in spectrometer time or in amounts of sample. This experiment will be particularly useful for measuring $^3J(NC'C_\alpha H)$ in polypeptides, which to date provides the only experimental way to estimate the backbone torsional angle, ψ, in solution.[11] For example, applying this technique to valinomycin we find a value for ^3J(N(D-Val)H(D-Hyv)) consistent with that previously reported[12] from ^{15}N-enriched valinomycin.[13]

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Registry No. Nitrogen-15, 14390-96-6; 6-methoxyquinoline, 5263-87-6; 2-pyrrolidinone, 616-45-5; N-methylacetamide, 79-16-3.

(5) Conventional ^{15}N spectra are of little value here for there is virtually no Overhauser enhancement of ^{15}N in this compound.

(6) A null value was also found for a similar $^4J_{NH}$ involving the (H(5),N-(1)) and (H(6),N(10)) pairs in 1,10-phenanthroline.

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(10) For the experiment described here the principal limitation on the resolution in the F_1 or J dimension appears to be dephasing of the ^{15}N coherence in t_1 by the "random-field" relaxation of the protons which are scalar coupled to ^{15}N (Shoup, R. R.; VanderHart, D. L. *J. Am. Chem. Soc.*, **1971**, *93*, 2053–2054; and Vold, R. R.; Vold, R. L. *J. Chem. Phys.* **1976**, *64*, 320–332), and this will be the subject of a separate publication. As noted in ref 3, a secondary limitation arises when the selectively flipped proton is tightly coupled to other protons. Some selectivity may be lost and the splitting patterns in the J dimension may contain extra lines. See, for example: Bodenhausen, G.; Freeman, R.; Morris, G. A.; Turner, D. L. *J. Magn. Reson.* **1977**, *28*, 17–28.

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(13) It might be expected that this technique will also be useful in other cases where multiple couplings have previously prevented spectral analysis, e.g., oligonucleotides, nitrogenous carbohydrates, and alkaloids.

Vibrational Circular Dichroism in (*S*)-(−)-Epoxypropane. Measurement in Vapor Phase and Verification of the Perturbed Degenerate Mode Theory

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Vibrational circular dichroism (VCD)[1] and Raman optical activity (ROA)[2] are recently developed spectroscopic techniques and are gaining increased attention for deducing molecular stereochemistry. In order to relate the experimental VCD and ROA to configurational details, simple conceptual models are also developed.[3] Of these models the perturbed degenerate mode theory[2,4] emphasizes the optical activity in vibrational modes of a methyl group. In a chiral environment the degenerate modes of a methyl group can be split into individual components, and such degeneracy-lifted modes are predicted to exhibit bisignate optical activity with the sign order reflecting the configuration of the chiral center to which the methyl group is attached.

The antisymmetric stretching, deformation, and rocking modes are the three degeneracy-lifted pairs of vibrations for the methyl group in a chiral environment. Liquid-phase VCD associated with the former two types of modes has been examined in the literature[5] but that associated with rocking modes has not been reported so far. To avoid condensed-phase effects and for comparisons to theoretical predictions, either matrix isolation[6] or vapor phase VCD measurements would be most appropriate. Here we report the first vapor-phase VCD measurement to verify the aforementioned theoretical concept; also the VCD features observed in vapor phase are compared with those observed in liquid phase to examine the phase effects. This is also the first report of VCD in degeneracy-lifted methyl rocking modes.

The measurements are carried out on a Fourier-transform infrared spectrometer described elsewhere.[7] A higher sensitivity MCT detector with D^* = 2 × 10^{10} and operating range of 5000–720 cm^{-1} is employed in the present studies. Vapor-phase measurements are made with the sample held in a 5-cm gas cell with KBr windows. For measurements in liquid phase, a variable path length cell with a 25-μm path length is employed. The base line and instrumental artifacts in VCD spectra are eliminated by subtracting the spectra of a racemic sample from those of the enantiomer.

The methyl group modes of epoxypropane are identified through the comparison of its infrared absorption spectra (Figures 1 and 2) with those of ethylene oxide[8] and monodeuterated ethylene oxide.[9] The bands in liquid phase at 1456 and 1446 cm^{-1} are considered to be associated with the degeneracy-lifted antisymmetric methyl deformation modes; the intense band at 1407 cm^{-1} is associated with the symmetric methyl deformation mode; the

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