(18) Cholli, A. L.; Dumais, J. J.; Engel, A. K.; Jelinski, L. W. *Macromolecules* **1984**, *17*, 2399.
(19) Jeffrey, K. R.; Bloom, M.; Valic, M. I.; Higgs, T. P. *Chem. Phys. Lett.* **1976**, *42*, 390.
(20) Blinc, R.; Rutar, V.; Seliger, J.; Slak, J.; Smolij, V. *Chem. Phys. Lett.* **1977**, *48*, 576.
(21) Mehring, M. "High Resolution NMR in Solids"; Springer-Verlag: New York, 1983.
(22) Spiess, H. W.; Mahnke, H. *Z. Naturforsch* **1972**, *27A*, 1536.
(23) Eisenstadt[24,25] has discussed the situation of magnetization transfer between spin $^1/_2$ nuclei in the presence and absence of exchange. Such a treatment would be premature in the present case, as we observe single-exponential relaxation within the uncertainty of the data.
(24) Eisenstadt, M. *J. Magn. Reson.* **1980**, *38*, 507.
(25) Eisenstadt, M. *J. Magn. Reson.* **1980**, *39*, 263.

Exposure of Hydroxyl Groups in Phenol–Acetaldehyde Oligomers, As Investigated by Photo-CIDNP ^{1}H NMR and Infrared Spectroscopy

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ABSTRACT: A number of oligomers related to phenol–acetaldehyde novolac resins possessing different stereoregularity are investigated by conventional and photochemically induced dynamic nuclear polarization (photo-CIDNP) ^{1}H NMR and IR spectroscopy. Complete assignment of NMR spectra is achieved by double-resonance techniques, spin-echo multiplet selection, use of shift reagents, and comparison with spectra of two monomeric model compounds. For each oligomer, the spectral parameters can be directly related to the tacticity of the molecule (i.e., to the sequence of meso and racemic units). The photo-CIDNP technique provides information on the accessibility of the phenolic moieties. In both monomers access to the OH's is hindered. From the dimer to the pentamer, a gradual reduction of the exposure of the OH groups from the external rings is observed, whereas those from the inner rings are always accessible, irrespective of the number of units. This indicates the absence of the isodromic intramolecular H bonds which were observed in the X-ray structure. In the IR experiments the OH···OH absorption band shifts to lower frequencies and broadens by increasing the molecular weight. Combined with the photo-CIDNP results, this suggests a progressive strengthening of the H bonding of the outer functional groups. Two empirical rules are proposed, which correlate the intensity of the aromatic signals with the number of internal phenolic units.

Introduction

All-ortho alkylidene-bridged oligophenols (novolacs) have been the subject of several investigations.[3-5] IR studies have shown that in carbon tetrachloride these molecules adopt well-defined conformations, involving OH---OH intra- and intermolecular hydrogen bonds.[6,7] The X-ray structure analysis of a number of oligomers indicates that the conformation in the crystal is mainly determined by an isodromic, intramolecular H-bonding system, formed by the phenolic functional groups.[5] The H-bond stabilization defines two domains, one highly polar, containing all OH groups, the other strongly hydrophobic, in which the aromatic rings form a lipophilic matrix.

The present communication is focused on the aromatic resonances of a number of oligophenols (number of internal rings $0 < n < 3$) having different steric regularity. The accessibility of the phenolic groups is investigated by photochemically induced dynamic nuclear polarization (photo-CIDNP) and IR spectroscopy, in order to obtain some evidence on the molecular structure, in particular on the stabilizing role of the hydrogen bonds.

Materials and Methods

The two monomers and the oligomers in this study were obtained as described elsewhere.[5] The methyl ester of 3-*N*-(carboxymethyl)lumiflavin was the kind gift of Dr. F. Müller (Wageningen). C^{2}HCl$_3$ was from Merck Isotopes.

The conventional NMR spectra were recorded with a Bruker HX-270 spectrometer, controlled by an Aspect 2000 computer. Chemical shifts are quoted in ppm from internal tetramethylsilane (Me$_4$Si). Typically 64 scans were accumulated for each spectrum. The spin-echo experiments shown in Figure 6 were performed according to the pulse sequence (90°–t_1–180°–t_1–±90°–t_2–90°–acquisition), where t_1 is $1/2J$ and t_2 allows for partial relaxation.[8]

Photo-CIDNP spectra were obtained with a Bruker HX-360 spectrometer, also equipped with an Aspect 2000 computer. The sample concentrations ranged between 6 and 12 mM in C^{2}HCl$_3$. Difference spectra were obtained by taking "light" and "dark" free induction decays (see text) and subtracting the spectra after Fourier transformation. A Spectra Physics Model 171 argon ion laser was employed as the light source. A 0.6-s light pulse (4 W, multiline) was used, with a 0.05-s delay before the 90° rf pulse. Four scans were accumulated for each spectrum. All spectra were resolution enhanced via the Gaussian convolution.[9] The line at 7.23 ppm in the photo-CIDNP difference spectra results from incomplete cancellation of the CHCl$_3$ signal.

IR spectra were obtained with a Perkin-Elmer 457 spectrometer, the sample concentrations varying between 0.2 and 2.0 mM in C^{2}HCl$_3$. The cell paths ranged between 75 and 500 μ.

Results and Discussion

Resonance Assignment. The phenol–aldehyde oligomers of this study are listed in Chart I. The monomers I and I′ are models for inner and outer rings in the oligomers, respectively. Figure 1 shows the aromatic region of the ^{1}H NMR spectra of I and I′, after resolution enhancement. The axial symmetry of compound I prevents the observation of J couplings across more than three

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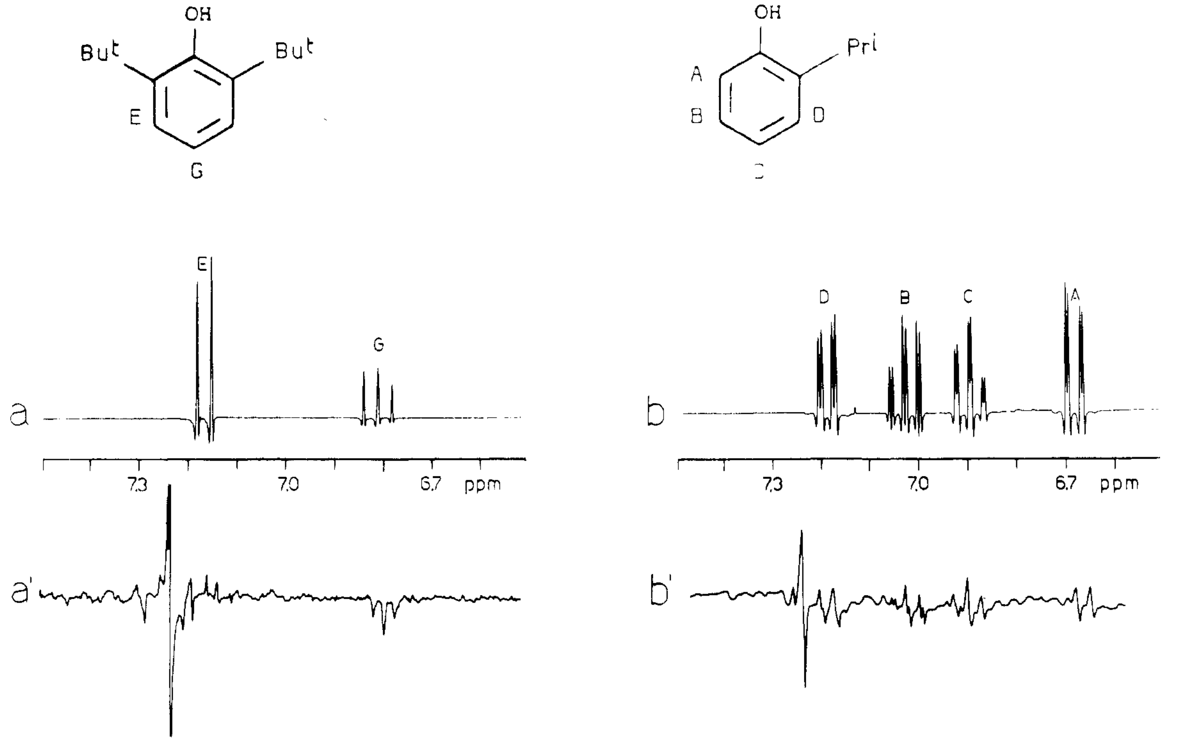


Figure 1. Aromatic region of the 270-MHz resolution enhanced ^1H NMR spectra and 360-MHz photo-CIDNP difference spectra of monomer I (a and a′, respectively) and I′ (b and b′, respectively) in C^2HCl_3.

bonds. The spectrum of I consists of a two-proton doublet at 7.17 ppm from the E protons, and of a one-proton triplet at 6.81 ppm, from the G proton, para to the phenolic function (Figure 1a, Chart I). The spectrum of I′ consists of two doublets (from A and D protons, Chart I) and two triplets (from B and C protons); each multiplet is further split, owing to meta interactions (Figure 1b). The doublet at 6.68 ppm is coupled to the triplet at 7.03 ppm, and the doublet at 7.19 ppm to the triplet at 6.89 ppm. To assign specifically doublets and triplets to the A–D protons, spectra have been recorded in the presence of various amounts of tris(2,2,6,6-tetramethylheptane-3,5-dionato)europium(III) $[Eu(DPM)_3]$; the only multiplet which exhibited an appreciable shift (to lower fields) was the doublet at 6.68 ppm, hence assigned to A, ortho to the OH group. This assignment was confirmed by the removal of a long-range coupling in both multiplets from C and D protons, following irradiation of the resonance from the CH at the ethylidene group, near 3.2 ppm. The spectra shown in Figure 1 are the basis for the interpretation of the aromatic resonances of the six oligomers listed in Chart I.

Figure 2a shows the spectrum of dimer II. By comparison of Figures 1 and 2, it is readily observed that the spectrum of II (Figure 2a) is essentially identical with the spectrum of monomer I′ (Figure 1b): in the dimer a plane of symmetry is present, which makes the two rings equivalent from the NMR standpoint. The proton assignments in Figure 2, made by analogy and based on the titration of I′ with the shift reagent, were confirmed by the photo-CIDNP experiments, which will be described below.

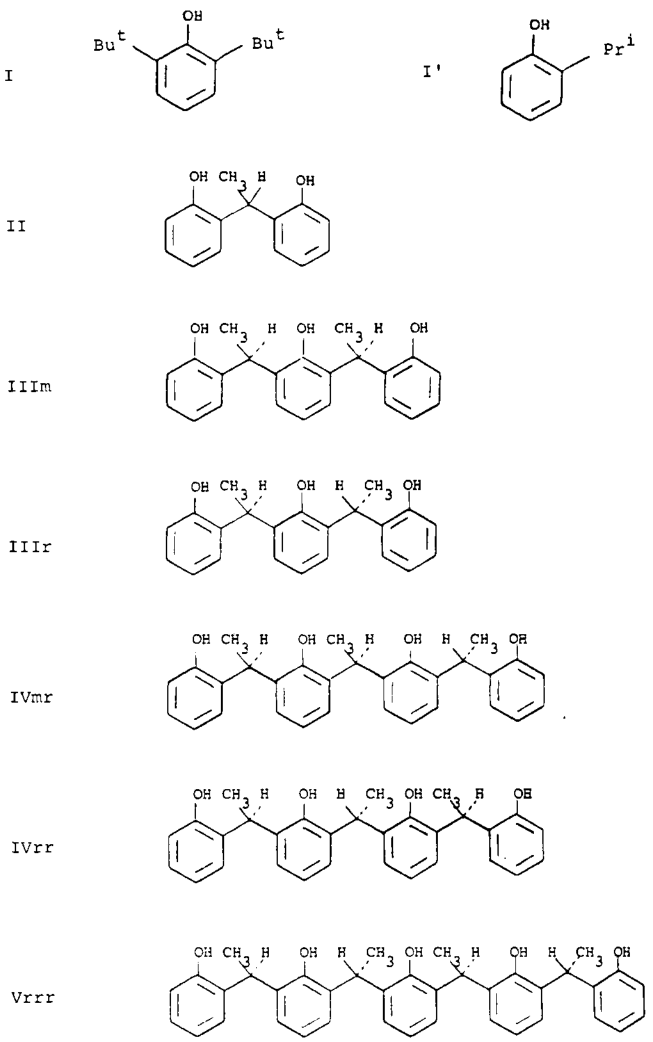
Trimers IIIr and IIIm differ in the configuration of the tertiary carbons at the ethylidene bridges, and this reflects on the symmetry of the molecule: in IIIr the outer rings are made equivalent by a C_2 axis, whereas in IIIm they are related through a plane of symmetry. The spectrum of trimer IIIr (Figure 3a) essentially results from the sum of the spectra of the separate monomers I and I′, with statistical weights one and two, respectively. At 270 MHz, the B and C protons become isochronous in the spectrum of trimer IIIm (Figure 3b). The accidental degeneracy causes second-order effects which complicate the resonance pattern of the protons from the outer rings in such a fashion that the observed splittings are no longer directly related to the coupling constants. The spin system has been simulated with the *J* values measured in the IIIr isomer, and the result is shown above the experimental spectrum.

The IVrr and IVmr tetramers differ in that the former has a plane of symmetry, whereas the latter is asymmetrical. This doubles the number of resonances in the spectrum of IVmr (Figure 4b), with respect to the spectrum of IVrr (Figure 4a). It has to be noticed that, although I is still a good model for the inner rings, in the tetramers the protons meta to the phenolic groups become nonequivalent within the same ring (E,F, Figure 4a; E,E′,F,F′, Figure 4b). All assignments of the tetramer resonances were confirmed by double-resonance experiments, as they were for all compounds studied in the resent communication.

The spectrum of the pentamer Vrrr is shown in Figure 5a. The resonance assignment was made by comparison with the spectra of the smaller oligomers, double-resonance, spin-echo multiplet selection, and photo-CIDNP experiments. Although the first two criteria were per se sufficient for a complete assignment, the spin-echo experiments shown in Figure 6 confirmed the triplet/doublet nature of the multiplets,[8] and the photochemical experiments, combined with homonuclear decoupling (Figure 5, a′ and a″) made it possible to distinguish between G and I triplets, otherwise degenerate at 270 MHz (see below).

Photo-CIDNP Experiments. The photo-CIDNP method has been used to investigate the access of a photoexcited flavin dye to the phenolic OH groups. By brief laser irradiation the dye, added to the solution, is excited to a singlet state, which is followed by rapid intersystem crossing to the triplet state.[10] Then, a radical pair can be formed, the back-reaction of which leads to nuclear spin

Chart I



polarization resulting in strong and specific enhancement of the NMR signals. Alternate light and dark spectra are collected, which can be subtracted to give the neat CIDNP effect. A phenolic derivative, whose OH is exposed to the dye, shows strong emission (negative signals in the difference spectrum) for the protons ortho and para to the OH group, and a weak absorption (positive signals) for the meta protons. The polarization is caused by a reversible hydrogen atom transfer from the phenolic OH to the photoexcited flavin, and its sign (emission or absorption) can be predicted from the spin density distribution and from the *g* factors of the intermediate radicals.[11] Since, for hydrogen atom abstraction, contact is necessary between the dye and the OH group, the method tests for exposure of the phenolic moiety. In other words, the phenolic derivative can only be polarized when the OH is freely accessible to the dye, whereas, if this group is involved in H bonds or sterically hindered from direct contact with the flavin, the CIDNP effects is no longer observed.

The photo-CIDNP spectrum of monomer I has been previously obtained by Schilling in carbon tetrachloride, using benzophenone as a hydrogen-abstracting reagent,[12] and shows weak absorptions for the meta signals and strong emission for the para signals. In contrast, in the presence of flavin dye, only a small enhancement is observed for the triplet corresponding to the para proton (Figure 1a′). The failure to observe intense polarization might indicate that steric hindrances, deriving from the *tert*-butyl moieties in both ortho positions, prevent the accessibility of the OH group to the flavin, but not to benzophenone.

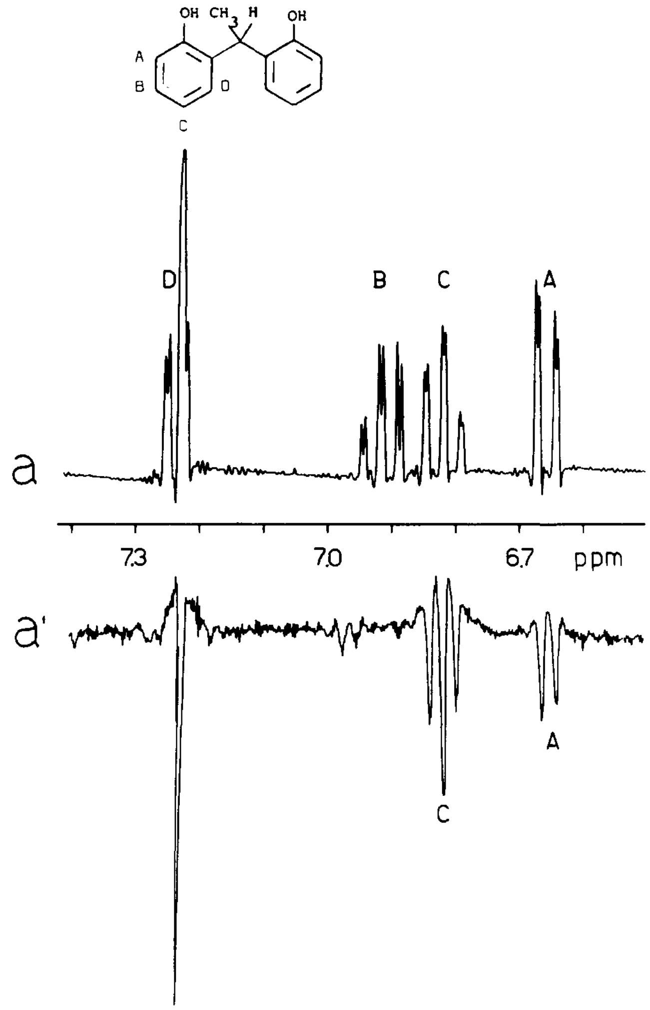


Figure 2. Aromatic region of the 270-MHz resolution enhanced spectrum (a) and 360-MHz photo-CIDNP difference spectrum (a′) of dimer II in C^2HCl_3.

No photo-CIDNP effect is seen at all for the monomer I′ (Figure 1b′). This suggests that the phenolic group is not exposed to the dye, owing to the presence of H bonds and (or) steric hindrance.

In the photo-CIDNP spectrum of the dimer (Figure 2a′), the two symmetrically equivalent aromatic rings exhibit strong emissive lines for the A doublet (ortho protons) and the C triplet (para protons), suggesting full accessibility of the OH groups to the photochemical probe.

Trimers IIIr and IIIm exhibit a similar photo-CIDNP effect (Figure 3, a′ and b′), i.e., an absorptive doublet at ca. 7.2 ppm, corresponding to the E (meta) protons of the internal ring, and a strong emissive triplet at ca. 6.9 ppm from the G (para) protons at the same ring. The latter assignment was tested by selective irradiation of the E doublet during a further CIDNP experiment (not shown): a neat singlet was recovered in the difference spectrum, showing that only the G protons contribute to the triplet observed in the difference spectra (Figure 3, a′ and b′). A small, negative signal is also observed for the A protons in the photo-CIDNP difference spectra of both IIIm and IIIr, whereas the para (C) protons of the external rings do not give any appreciable effect.

Similarly to what was observed for the trimers, in both tetramers IVmr and IVrr only the internal rings exhibit a polarization pattern characteristic of free and accessible OH groups (emissive triplets for the para protons and

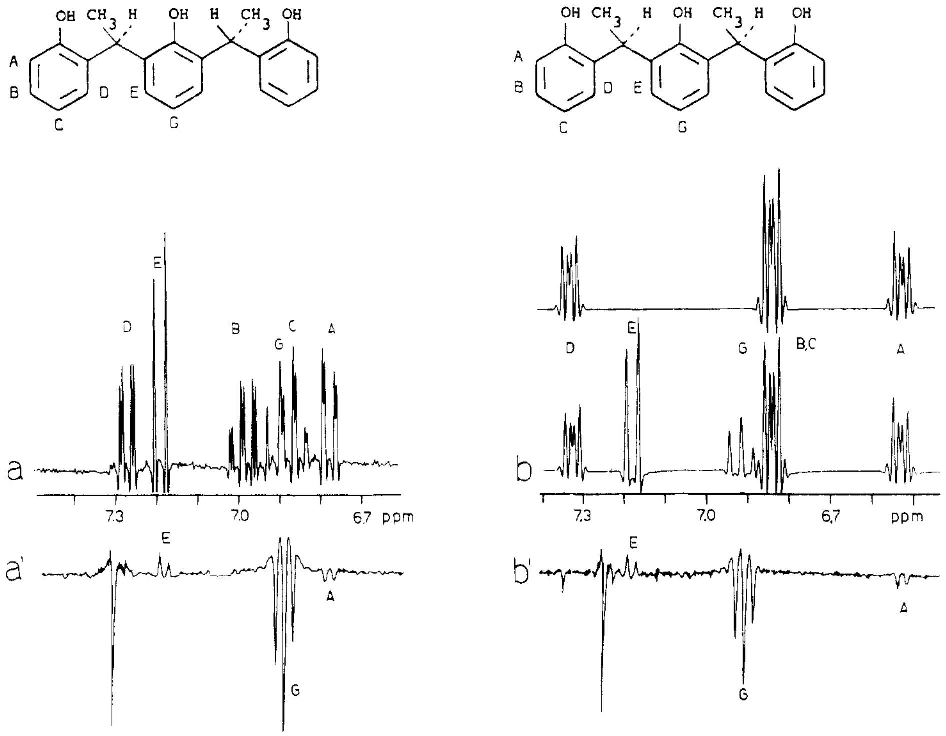


Figure 3. Aromatic region of the 270-MHz resolution enhanced spectra and 360-MHz photo-CIDNP difference spectra of trimer IIIr (a and a′) and IIIm (b and b′) in C^2HCl_3. For IIIm, above the experimental spectrum (b) is shown the computer simulation of the ABCD proton resonances.

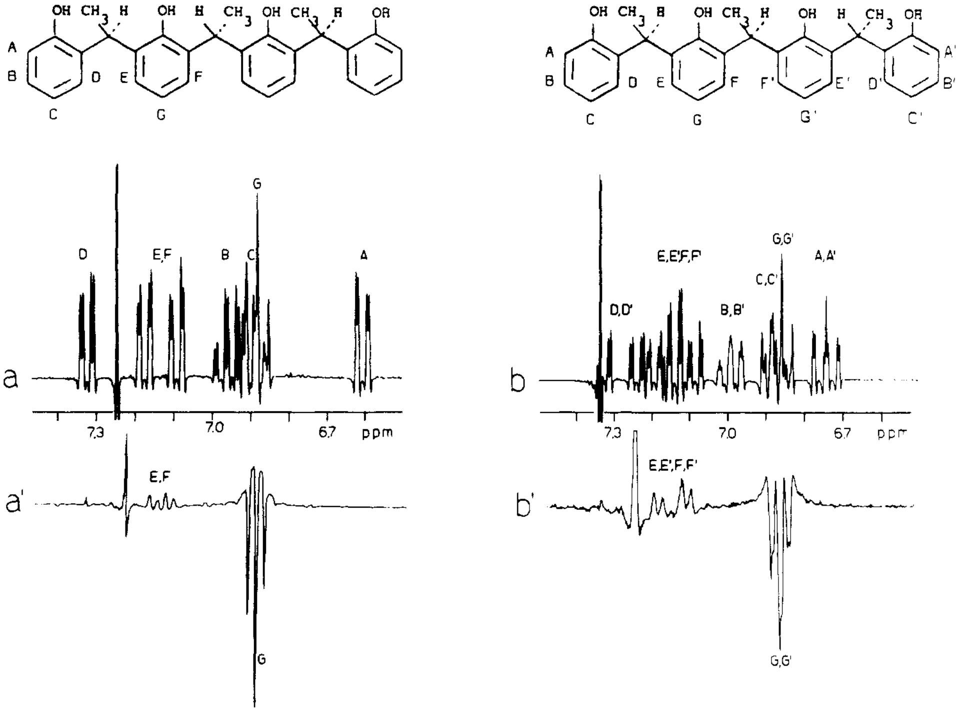


Figure 4. Aromatic region of the 270-MHz resolution enhanced spectra and 360-MHz photo-CIDNP difference spectra of tetramer IVrr (a and a′) and IVmr (b and b′) in C^2HCl_3.

absorptive doublets for the meta protons, Figure 4, a′ and b′), whereas no significant enhancement is detected for the protons of the external rings. It is noticeable that the G,G′ triplets in the atactic tetramer IVmr, degenerate in the reference spectrum recorded at 270 MHz (Figure 4b), become nonequivalent at 360 MHz, in the photo-CIDNP difference spectrum (Figure 4b′).

Consistently with all the above observations, the pentamer Vrrr gives an enhancement pattern (Figure 5a′) which indicates once more that only the three internal rings may interact with the flavin molecule. As for the tetramer IVrr, the triplets from the two types of para protons from the internal rings (G,I) coincide at 270 MHz (Figure 5a), whereas they are split at 360 MHz (Figure 5a′). During the photo-CIDNP experiment, setting the decoupler frequency in the center of the H doublet at 7.1 ppm, slightly off-resonance from the multiplets of the other meta protons from the internal rings (E,F), produced the coalescence of the multiplet at 6.8 ppm into two singlets: one sharp, corresponding to complete decoupling of the I triplet

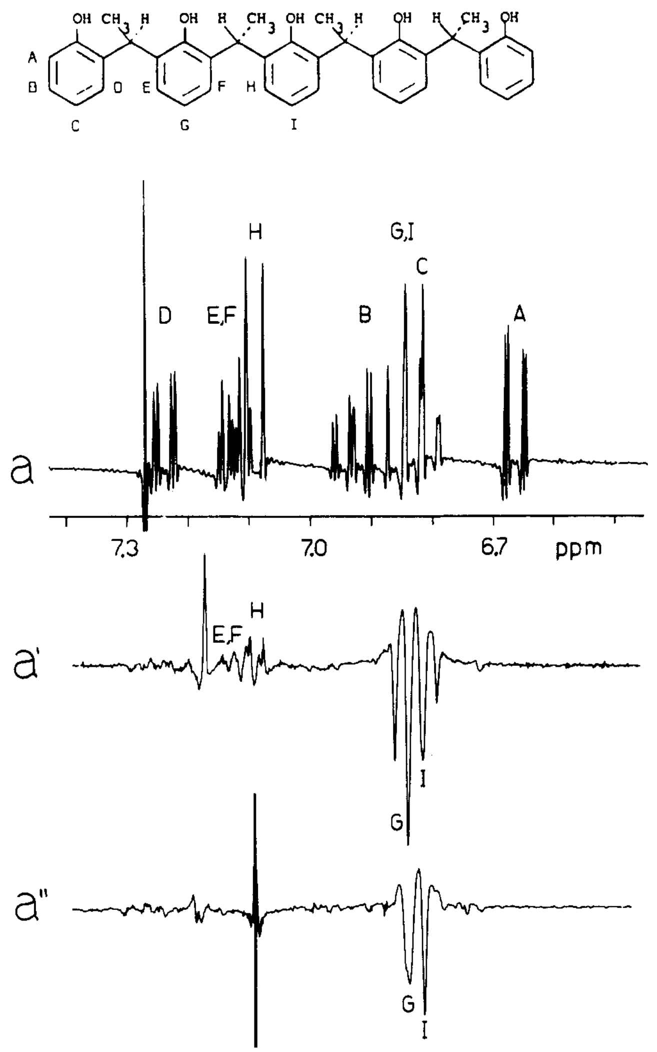


Figure 5. Aromatic region of the 270-MHz resolution enhanced spectrum (a), 360-MHz photo-CIDNP difference spectrum (a′), and homonuclear decoupled photo-CIDNP difference spectrum (a″) of pentamer Vrrr in C^2HCl_3.

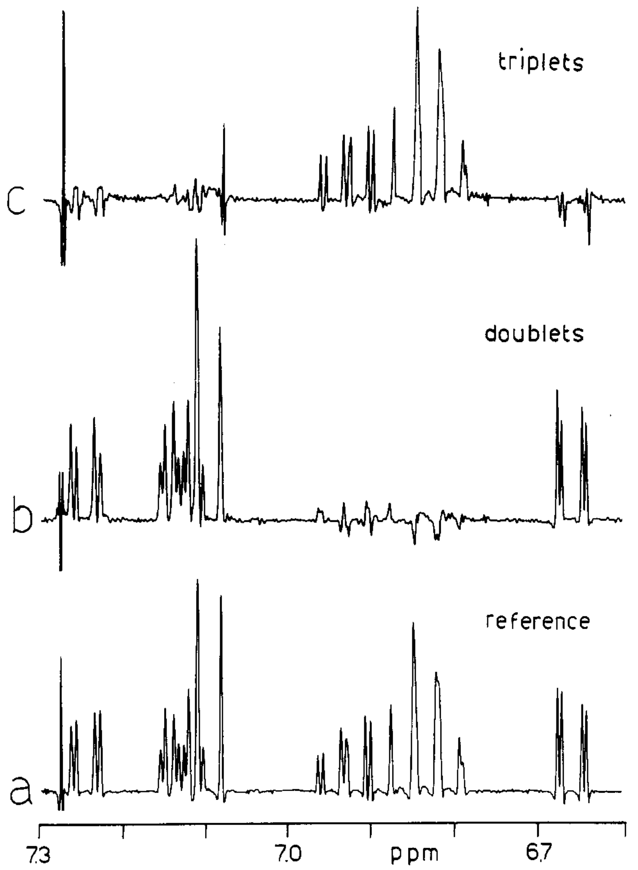


Figure 6. Spin-echo experiments on the aromatic resonances of pentamer Vrrr at 270 MHz: (a) reference spectrum, (b) partially relaxed echo, doublets only, (c) partially relaxed echo, triplets only.

Table I
Hydroxyl IR Stretching Absorptions (cm^{-1}) in C^2HCl_3

compd	free		bonded
I	3640 (s)		
I′	3650	3590	3450
II		3590 (s)	3450
IIIr		3590	3300
IIIm		3590	3300
IVrr	3650	3590	3300
IVmr	3650	3590	3300
Vrrr	3650 (w)	3590	3300 (vb)

[a] w = weak, vb = very broad, s = sharp.

from the H doublet, and one broader, owing to noncomplete removal of the interaction between the E,F and the G protons (Figure 5a″). This experiment confirms the previous interpretation of the resonance pattern in the spectrum shown in Figure 5a′.

IR Experiments. The infrared absorption band arising from the OH valence vibration is one of the earliest known and most studied of any. In strongly dilute solutions of phenols in an inert solvent, i.e., in a situation in which H bonding is highly unfavored, a single, narrow band for the free OH is observed at about 3610 cm^{-1}.[13] As the concentration of phenol is increased, several H-bonded species are formed, and a number of broad signals appear at lower frequencies, with progressively growing intensity.[14] In chloroform solution, where some interaction with the solvent is expected, the monomeric model compound I is present in a predominant form, as it gives a strong and sharp band at 3640 cm^{-1}. This band is still in the spectral region characteristic of OH groups which are not H bonded, but partially hindered: the bulky substituents in both the ortho positions prevent any intermolecular association. In contrast, monomer I′ exists as an equilibrium among several species: a strong and broad band is observed at 3450 cm^{-1}, corresponding to a bonded OH (Table I). Two additional, weak bands at 3590 and 3650 cm^{-1} are assigned to free OH's and to OH's which are not H bonded, but partially hindered, respectively.[6] For both monomers, the IR results are well consistent with the lack of appreciable photo-CIDNP effects, suggesting that the steric requirements for the photoreaction are not satisfied.

The dimer exhibits only two absorptions in the OH region of the IR spectrum, i.e. one (sharp) at 3590 cm^{-1}, corresponding to a free OH, and one (broad) at 3450 cm^{-1}, due to an intramolecular H bond (Table I). These results are in good agreement with those previously obtained by Cairns and Eglinton for the homologous dimer from phenol–formaldehyde condensation.[6]

Two bands are also observed for both IIIr and IIIm trimers. One, sharp and weak, at 3590 cm^{-1}, corresponds to a free OH (as for the dimer); the other, broad and more intense, at 3300 cm^{-1}, suggests the presence of intermolecular H bonds. The band at 3300 cm^{-1} is also found in both tetramers IVrr and IVmr (Table I). For both compounds the signal was strongly dependent on concentration, in the range 0.2–2.0 mM. As shown in Figure 7 for compound IVrr, when the concentration of tetramer is increased, the "association" band (OH's bonded) grows at the expense of the monomer band at 3600 cm^{-1} (OH free), indicating

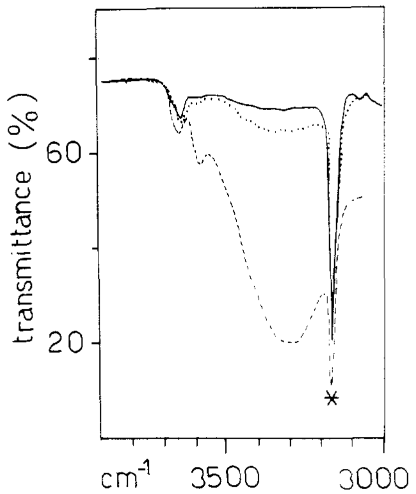


Figure 7. Infrared spectrum in the O–H stretch region of tetramer IVrr: (—) 0.2, (···) 0.4, and (---) 2.0 mM in C^2HCl_3.

the presence of intermolecular interactions. In addition, both tetramers show a weak band at 3650 cm^{-1}, arising from OH's free, but hindered.

Finally, the pentamer Vrrr shows exactly the same bands observed in the tetramers, the association signal being even broader and more intense.

Conclusions

Besides any structural implication, a detailed assignment of the aromatic resonances in ^1H NMR spectra of novolac-type oligomers is of particular interest from the analytical standpoint. The intensity of the aromatic signals is directly related to the number of phenolic rings, a feature which makes straightforward the determination of the molecular weight of a given oligomer. A relation was earlier proposed, based on ^{13}C NMR intensities.[4]

The number of internal phenolic units n is given by the expression $n = 2(B + C + G + I)/A - 4$ where A, B, and C are the intensities of the ortho, meta, and para proton resonances from the external units, respectively, and G and I are the intensities of the para proton resonances from the internal rings (see Chart I). As can be seen in the spectra of the various oligomers (Figures 1–5), B, C, G, and I multiplets overlap among each other, but are well separated from A; hence, n is readily obtained from the ratio between the integrated areas of the two spectral regions.

In principle, n can be as well calculated by comparing the intensity of the meta resonances from the internal units (E, F, and H) with that of the isolated D multiplet: $n = (E + F + H)/D$. This equation is as good as the previous one, but has the disadvantage that it cannot be used if the isotopic impurity from C^2HCl_3 overlaps with the D multiplet, preventing its integration (see, e.g., Figure 2a).

The laser photo-CIDNP experiments performed on the two monomers and on the various oligomers demonstrate that the OH moieties are not equally accessible to the flavin dye. In both monomers the hydroxyl groups are not exposed, owing to steric hindrance (I) or to self-association (I′), according to the IR results. From the dimer to the pentamer, the OH exposure of the external units appears to be strongly reduced, suggesting a tendency to associate through the hydroxyls of the external rings, as the molecular weight increases. In contrast, the OH groups of the inner rings are always exposed to the flavin, irrespective of the size of the oligomers. This implies the absence of the isodromic intramolecular H bonds, which were observed in the solid state. An attempt to predict the positions of the various resonances in the spectra of both trimers via ring-current shift calculations[15] performed by using the atomic coordinates from the crystal structure[5] failed, in that the calculated chemical shifts were quite different from the experimental ones; no correspondence between the two sets of data could be found at all, confirming the substantial discrepancy between the solid state and the solution association behavior.

These results are confirmed by the characteristics of the IR signal assigned to the bonded OH's. In the solid state, the increase of the oligomer size from two to five units results in an appreciable upward frequency shift (from 3200 to 3340 cm^{-1}) of the hydroxyl band,[3] probably because of a decreased polymeric association of the higher oligomers. In contrast, in C^2HCl_3 solution, the OH---O band shifts to lower frequencies (from 3450 to 3300 cm^{-1}), with increasing molecular weight. The shift is accompanied by a considerable line broadening, and a concomitant intensity rise, indicative of a strengthening of the hydrogen bonds.

Finally, on the basis of the present results it can be inferred that the conformation suggested by Cairns and Eglinton for the phenol–formaldehyde tetranuclear derivative in CCl_4[6] does not apply to the acetaldehyde homologues in chloroform. In this conformation the four hydroxyl groups would be involved in a closed ring of intramolecular hydrogen bonds, in which they all become equivalent (either all-exposed, or all-nonexposed). This hypothesis is consistent neither with the photo-CIDNP nor with the conclusions reached on the basis of the IR experiments.

Registry No. I, 128-39-2; I′, 88-69-7; II, 96212-27-0; IIIm, 87804-19-1; IIIr, 87804-20-4; IVmr, 87804-21-5; IVrr, 87860-10-4; Vrrr, 96346-13-3; (acetaldehyde)·(phenol) (copolymer), 27814-11-5.

References and Notes

(1) This work was presented in part at the Sixth International Meeting on NMR Spectroscopy, Edinburgh, Scotland, July 1983.
(2) (a) Istituto di Chimica della Macromolecole, CNR, Milano. (b) Istituto di Chimica Organica, Università di Parma. (c) Physical Chemistry Laboratory, University of Groningen.
(3) Casiraghi, G.; Cornia, M.; Sartori, G.; Casnati, G.; Bocchi, V.; Andreetti, G. D. *Makromol. Chem.* **1982**, *183*, 2611–33.
(4) Casiraghi, G.; Cornia, M.; Ricci, G.; Balduzzi, G.; Casnati, G.; Andreetti, G. D. *Makromol. Chem.* **1983**, *184*, 1363–78.
(5) Casiraghi, G.; Cornia, M.; Ricci, G.; Casnati, G.; Andreetti, G. D.; Zetta, L. *Macromolecules* **1984**, *17*, 19–28.
(6) Cairns, T.; Eglinton, G. *J. Chem. Soc.* **1965**, 5906–13.
(7) Bennet, W. S.; Eglinton, G.; Kovac, S. *Nature (London)* **1967** *214*, 776–80.
(8) Lecomte, J. T. J.; De Marco, A.; Llinâs, M. *Biochim. Biophys. Acta* **1982**, *703*, 223–30.
(9) Ferrige, A. G.; Lindon, J. C. *J. Magn. Reson.* **1978**, *31*, 337–40.
(10) Kaptein, R. In "Biological Magnetic Resonance"; Berliner, L. J., Reuben, J., Eds.; Plenum Press: New York, 1982; Vol. 4, p 145.
(11) Kaptein, R. *J. Chem. Soc., Chem. Commun.* **1971**, 732–3.
(12) Schilling, M. L. M. *J. Am. Chem. Soc.* **1981**, *103*, 3077–81.
(13) Bellamy, L. J. In "The Infra-red Spectra of Complex Molecules"; Chapman and Hall: London, 1975; Vol. 1, p 107.
(14) Hall, A.; Wood, J. L. *Spectrochimica Acta, Part A* **1967**, *23*, 2657–62.
(15) Johnson, C. E.; Bovey, F. A. *J. Chem. Phys.* **1958**, *29*, 1012–4.