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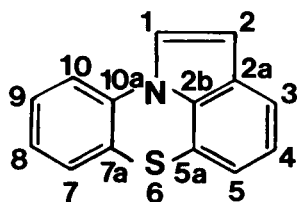
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Total assignment of the  $^{13}\text{C}$ -nmr spectrum of the novel tetracyclic phenothiazine, pyrrolo[3,2,1-*kl*]phenothiazine is described. Assignments were determined from model systems,  $^1\text{H}$ - $^{13}\text{C}$  spin-coupling behavior in conjunction with selective excitation techniques and spin-lattice ( $T_1$ ) relaxation measurements. The anisotropic reorientation of this ring system via a principal axis passing through the center of the molecule, which provides a qualitative basis for signal discrimination, is also discussed.

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Syntheses of various tetracyclic fused ring analogs of the phenothiazine ring system have appeared in the recent literature (4-16). Despite the number of such compounds which have been reported, there have been no studies done on the effects of fusing heterocyclic or benzenoid systems on the chemical shifts of the phenothiazine nucleus. Further, there have also been no total assignments of the  $^{13}\text{C}$ -nmr spectra of any members of this interesting family of related and potentially important compounds. We therefore would now like to report the total assignment of the  $^{13}\text{C}$ -nmr spectrum of pyrrolo[3,2,1-*kl*]phenothiazine (**1**) (13) based on a concerted application of spectroscopic techniques which includes an application of a new model of anisotropic reorientation (17) as a qualitative discriminatory criterion.

From a cursory examination of the  $^{13}\text{C}$ -nmr spectrum of **1**, shown in Figure 1, only one resonance could be unequivocally assigned from simple chemical shift information. Specifically, C2, in the pyrrole portion of the molecule, which has essentially vinyl character, was assigned to the resonance observed at  $\delta = 104.95$ , this chemical shift in good accord with the corresponding carbons of both pyrrole (**2**) and indole (**3**), whose resonances are at  $\delta$  108.4 (18) and 102.6 (19), respectively.

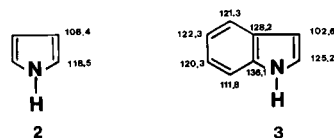


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Preliminary sorting of the protonated and non-protonated resonances of **1** was achieved by taking advan-

tage of the expected longer  $T_1$  relaxation times of the latter. Based on this premise, the spectrum shown in Figure 1 was obtained using a relatively large flip angle ( $\alpha = 45^\circ$ ) and a relatively short interpulse delay (3 seconds) which had the net effect of permitting only partial relaxation of the non-protonated resonances. A consequence of these acquisition conditions was that the non-protonated resonances of **1**, as shown in Figure 1, were of significantly reduced signal intensity relative to their protonated counterparts. Thus, based on this experiment, the resonances observed at  $\delta$  133.53, 130.86, 127.52, 119.75 and 115.95 were all delineated as non-protonated carbons. Furthermore, comparison of these chemical shift data with the reported chemical shifts of phenothiazine (**4**) (20) and indole (**3**) (19) helped to further sub-group these resonances.

Based on comparison with phenothiazine chemical shifts (20), the resonances observed at  $\delta$  119.75 and 115.95 for **1** were assigned to be the sulfur bearing carbon resonances. Although no specific assignment within this pair could be made solely from the chemical shift data, unequivocal assignment was, however, possible from the spin-coupling constant studies detailed below. While the preceding pair of resonances was in reasonably good accord with their phenothiazine counterpart, the nitrogen bearing carbon resonances exhibited a considerable



disparity relative to their phenothiazine counterpart at  $\delta$  141.7. Thus, a preliminary assignment of the resonances observed at  $\delta$  133.53 and 130.86 was made to the nitrogen bearing carbons C2b and C10a, this assumption being

based on the relatively good agreement of the C2a resonance at  $\delta$  127.52 with its counterpart in indole (3) (19). It should, however, be noted that caution is to be exercised in making such assignments since such situations frequently lead to a permutation of assignments unless additional means of confirmation of the assignments are also employed. In this case, however, unequivocal assignment of the three resonances in this latter group was possible from arguments derived from spin-lattice relaxation behavior, which is also discussed below.

Following the segregation of resonances into protonated and non-protonated sub-groups, no further assignments of specific resonances were possible solely from the chemical shift information available which necessitated that the proton coupled spectrum be investigated. Despite the wealth of spectroscopic information contained in a spin-coupled spectrum, as shown in Figure 2, these spectra are seldom fully interpreted because of their inherent complexity. In particular,  $^1\text{H}$ - $^{13}\text{C}$  spin-coupled spectra obtained under gated decoupling acquisition conditions (21), are routinely subject to spin-multiplet overlapping as a result of the magnitude of the primary ( $^1\text{J}_{\text{CH}}$ ) spin-coupling constants and the proximity of numerous  $^{13}\text{C}$ -resonances. The net result of these effects is to make the complete dissection of all coupling constants contained in fully coupled

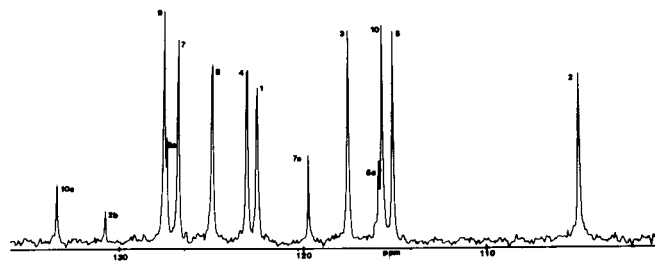


Figure 1. Decoupled 25.2 MHz  $^{13}\text{C}$ -nmr spectrum of **1** in deuteriochloroform.

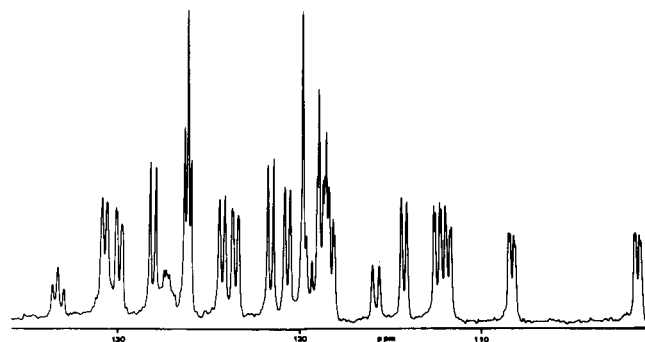
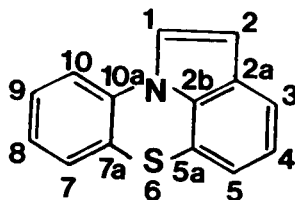


Figure 2.  $^1\text{H}$ - $^{13}\text{C}$  spin coupled spectrum of **1** acquired under gated decoupling conditions.

Table I

$^{13}\text{C}$ -nmr Chemical Shift Assignments and  $^1\text{H}$ - $^{13}\text{C}$  Spin-Coupling Constants of Pyrrolo[3,2,1-kl]phenothiazine (**1**) in Deuteriochloroform



carbon	$\delta$	$^1\text{J}_{\text{CH}}$	$^1\text{J}_{\text{CH}}$	$^3\text{J}_{\text{CH}}$
C10a	133.53	---	---	$^3\text{J}_{\text{C}_{10\text{a}}\text{J}_7} = 7.46$
		---	---	$^3\text{J}_{\text{C}_{10\text{a}}\text{H}_9} = 7.46$
C2b	130.86	---	---	$^3\text{J}_{\text{C}_{2\text{b}}\text{H}_3} = 7.69$
		---	---	$^3\text{J}_{\text{C}_{2\text{b}}\text{H}_5} = 7.69$
C9	127.67	$^1\text{J}_{\text{C}_9\text{H}_6} = 163.52$	---	$^3\text{J}_{\text{C}_9\text{H}_7} = 6.76$
C2a	127.47	---	$^2\text{J}_{\text{C}_{2\text{a}}\text{H}_2} = 2.94$	$^3\text{J}_{\text{C}_{2\text{a}}\text{H}_4} = 4.86$
C7	126.92	$^1\text{J}_{\text{C}_7\text{H}_7} = 161.98$	$^2\text{J}_{\text{C}_7\text{H}_8} = 1.49$	$^3\text{J}_{\text{C}_7\text{H}_9} = 7.92$
C8	125.03	$^1\text{J}_{\text{C}_8\text{H}_8} = 164.58$	---	$^3\text{J}_{\text{C}_8\text{H}_{10}} = 7.72$
C4	123.14	$^1\text{J}_{\text{C}_4\text{H}_4} = 160.96$	---	---
C1	122.61	$^1\text{J}_{\text{C}_1\text{H}_1} = 188.58$	$^2\text{J}_{\text{C}_7\text{H}_2} = 9.66$	---
C7a	119.75	---	---	$^3\text{J}_{\text{C}_{7\text{a}}\text{H}_8} = 7.54$
		---	---	$^3\text{J}_{\text{C}_{7\text{a}}\text{H}_{10}} = 7.54$
C3	117.58	$^1\text{J}_{\text{C}_3\text{H}_3} = 162.46$	---	$^3\text{J}_{\text{C}_3\text{H}_5} = 7.76$
C5a	115.95	---	---	$^3\text{J}_{\text{C}_{5\text{a}}\text{H}_4} = 9.21$
C10	115.73	$^1\text{J}_{\text{C}_{10}\text{H}_{10}} = 162.34$	$^2\text{J}_{\text{C}_{10}\text{H}_9} = 2.25$	$^3\text{J}_{\text{C}_{10}\text{H}_8} = 8.09$
C5	114.14	$^1\text{J}_{\text{C}_5\text{H}_5} = 162.68$	$^2\text{J}_{\text{C}_5\text{H}_4} = 1.79$	$^3\text{J}_{\text{C}_5\text{H}_3} = 7.97$
C2	104.95	$^1\text{J}_{\text{C}_2\text{H}_2} = 175.15$	$^2\text{J}_{\text{C}_2\text{H}_1} = 7.23$	$^3\text{J}_{\text{C}_2\text{H}_3} = 2.27$

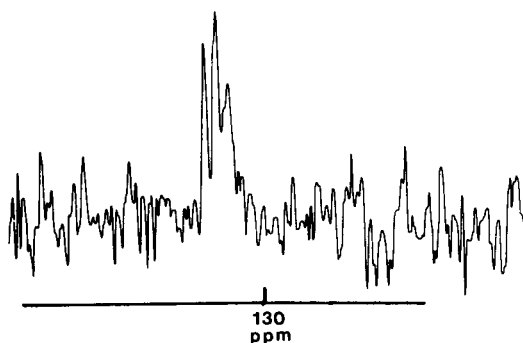


Figure 3. Selectively excited  $^{13}\text{C}$ -nmr subspectrum of the resonance for C2b with gated decoupling.

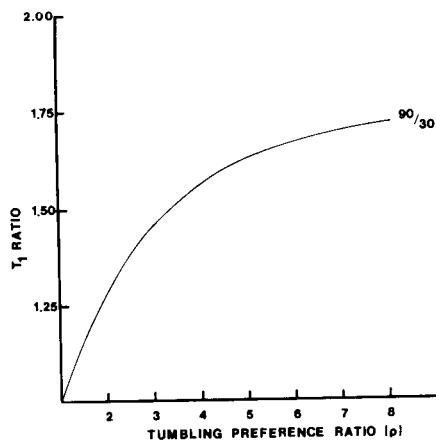
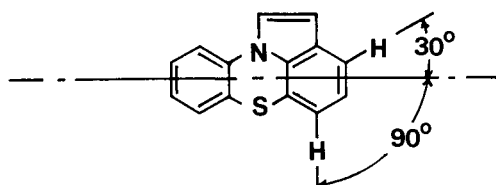


Figure 4. Calculated curve illustrating the relationship between the tumbling preference ratio ( $Q$ ) and the  $T_1$  relaxation ratio for carbons with C-H bond vectors oriented at  $30^\circ$  and  $90^\circ$ .

spectra an arduous task. These difficulties are, however, completely and conveniently circumvented by the selective excitation technique of Freeman and co-workers (22,23) which we have utilized extensively in our studies of various phenoxathiin analogs (24-28). The convenient feature of this technique is that it allows the examination of individual selectively excited sub-spectra, with full coupling information for each resonance in a molecule. Thus, utilizing this technique, four additional resonances contained in the  $^{13}\text{C}$ -nmr spectrum of **1** were assigned.

The first of the resonances, which was assigned on the

basis of coupling constant data, was the resonance corresponding to C1 in the pyrrole portion of the molecule. Spin-coupling constant data available for pyrrole (29) indicated that the corresponding resonance in **1** should have a primary coupling constant of approximately  $^1J_{\text{CH}} = 182$  Hz, which is considerably larger than the primary coupling constant of approximately 160-165 Hz normally encountered in benzenoid systems. Thus, by utilization of selective excitation with gated decoupling, the resonance at  $\delta = 122.61$  which exhibited a primary coupling  $^1J_{\text{C}_1\text{H}_1} = 188.58$  was assigned to C1. It should also be noted that C1 exhibited a large two bond coupling  $^2J_{\text{C}_1\text{H}_2} = 9.66$  Hz, characteristic of pyrrole and pyridine derived systems (24,26-28). However, because of the nature of the fusion of the pyrrole ring to the phenothiazine nucleus, no three bond coupling was possible in this system (Table I).

The second resonance assignable on the basis of spin-coupling data was that for C4 which, because of the fusion of the pyrrole ring to the phenothiazine nucleus, did not exhibit any three bond couplings. Thus, the resonance observed at  $\delta 123.14$ , which had only a primary coupling represented by the two most intense signals shown in Figure 2 ( $^1J_{\text{C}_4\text{H}_4} = 160.96$ ), was assigned to C4.

The two remaining resonances which were unequivocally assignable by spin-coupling constant information were the sulfur bearing carbon resonances C5a and C7a. Assignment of C5a, as with C4, was based on the relative number of three bond couplings which this resonance exhibited. Thus, C5a had only one three bond coupling,  $^3J_{\text{C}_{5a}\text{H}_3} = 9.21$  Hz, possible. In contrast, C7a, located in the unsubstituted portion of the phenothiazine system, had two equivalent three bond couplings,  $^3J_{\text{C}_{7a}\text{H}_8} = 7.54$  Hz and  $^3J_{\text{C}_{7a}\text{H}_{10}} = 7.54$  Hz giving rise to an apparent triplet as a result of the overlapping doublet of doublets. Based on this behavior, C5a assigned to the resonance observed at  $\delta 115.95$  while C7a was assigned to the resonance at  $\delta 119.75$ .

Although no additional assignments were possible from the spin-coupling constant data obtained from the selective excitation experiments, it is pertinent to discuss the remaining coupling constants since these include some rather unanticipated behavior which may be of diagnostic utility. Assignments for the resonances remaining were all derived from spin-lattice relaxation experiments in conjunction with chemical shift and coupling constant arguments as discussed below.

The first of the unusual coupling constants were those associated with the resonance for C2a assigned at  $\delta = 127.47$ . This particular resonance is unique in that it is one of two resonances shared between the pyrrole ring and the phenothiazine ring such that it could experience coupling from protons contained in both of these systems. In particular, C2a exhibits a two bond coupling,  $^2J_{\text{C}_{2a}\text{H}_2} = 2.94$  Hz and a three bond coupling,  $^3J_{\text{C}_{2a}\text{H}_4} = 4.86$  Hz.

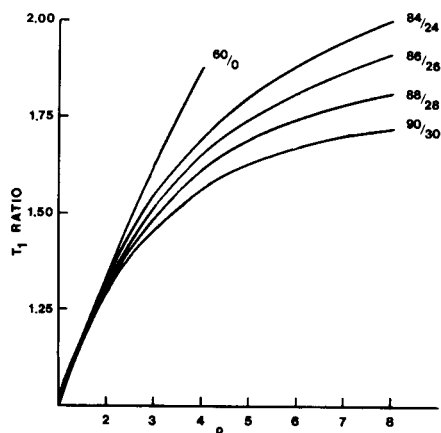
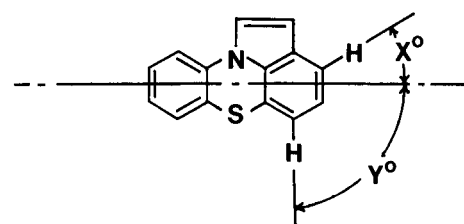


Figure 5. Calculated curves for various C-H bond vector orientations showing the similarity at low tumbling preference ratios. (Where X may assume values ranging from 24 to 30° and Y may assume values ranging from 84 to 90°. The 60/0 curve is shown solely for comparison.)

It is interesting that both of these coupling constants are somewhat smaller than normal, the former in pyrrole normally being about 4.6 Hz while three bond couplings are typically 7-8 Hz. No simple explanation is available for this behavior, although it could conceivably be approximated by an appropriately substituted indole system.

Coupling behavior for C2b is also unusual in that one three bond coupling, which would be anticipated for this resonance, is completely absent. Not surprisingly, the

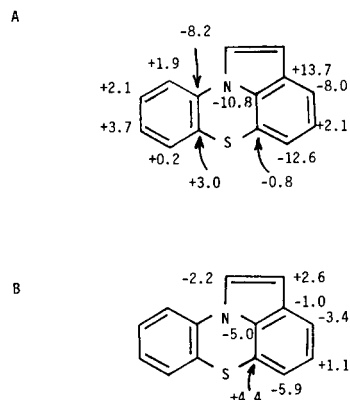


Figure 6. Chemical shift differences ( $\Delta\delta$  ppm) between pyrrolo[3,2,1-*k*]phenothiazine and phenothiazine (A) and indole (B).

resonances corresponding to a substitution pattern in this position of a tricyclic system would normally exhibit two three bond couplings. In the specific case of this resonance, these couplings would be  ${}^3J_{C_{2b}H_3}$  and  ${}^3J_{C_{2b}H_5}$ . In addition, because of the unique position of C2b, which is astride the fusion of the two ring systems, a third three bond coupling through the nitrogen atom,  ${}^3J_{C_{2b}H_1}$ , should also be in evidence. The resonance, however, appears in selective excitation subspectra (see Figure 3) as a simple overlapping doublet of doublets. Which of the specific couplings is missing and the reasons for its absence are open to speculation.

A third interesting example of coupling constant behavior is seen in the resonance for C2 at  $\delta = 104.95$ . In addition to the one bond coupling,  ${}^1J_{C_2H_2} = 175.15$  Hz and the two bond coupling,  ${}^2J_{C_2H_1} = 7.23$  Hz, this resonance also exhibits a three bond interring coupling which is considerably smaller than the normal three bond coupling. The specific coupling in question,  ${}^3J_{C_2H_3} = 2.27$  Hz, is assigned from comparison with the vinylic resonance, C3, of indole (3) which exhibited only the one

Table II

Calculated and Observed T<sub>1</sub> Relaxation Times for the Non-protonated <sup>13</sup>C-Nmr Resonances of I in Deuteriochloroform at 25.158 MHz and 33°

Resonance	$\delta$ (ppm)	NOE (1 + $\eta$ )	Relaxation Time (seconds)	
			Observed	Calculated (a)
C10a	133.53	1.81	35.02 ± 0.57	35.71
C2b	130.86	1.11	65.90 ± 0.67	67.09
C2a	127.52	2.13	26.34 ± 1.60	26.59 (b)
C5a	119.75	2.32	38.83 ± 1.62	42.74
C7a	115.95	1.90	41.11 ± 2.72	42.74

(a) Relaxation times were calculated using a correlation time,  $\tau = 3.9 \times 10^{-11}$  sec, computed from the overall average of the T<sub>1</sub> relaxation times for the protonated carbons using equation 1. (b) Assuming 2.2 Å to H2 and 2.0 Å to H3 based on a Dreiding model.

Table III

$T_1$  Relaxation Times of the Protonated  $^{13}\text{C}$ -Nmr Resonances of **1** in Deuteriochloroform at 25.158 MHz and 33°

Resonance	$\delta$ (ppm)	NOE (1 + $\eta$ )	Relaxation Time (seconds)	
			Inversion (a) Recovery	Progressive Saturation
9	127.67	2.61	1.10	1.11
7	126.92	3.10	1.30	1.26
8	125.03	2.81	1.03	1.05
4	123.14	3.04	1.05	1.10
1	122.61	2.74	1.11	1.23
3	117.58	2.90	1.07	1.12
10	115.73	2.82	1.26	1.28
5	114.14	3.05	1.26	1.26
2	104.95	3.03	1.17	1.24

(a)  $T_1$  Inversion - recovery data reduction was conducted using the three parameter fit program of J. G. Kowalewski, G. C. Levy, L. F. Johnson and L. Palmer, *J. Magn. Reson.*, **26**, 553 (1977).

bond and two bond couplings characteristic of the pyrrole ring. The unusual nature of the three bond coupling seen in this system is again a topic subject to speculation although it conceivably would be of some diagnostic utility in 2-substituted pyrrolophenothiazine assignments if it is still in evidence.

The final interesting aspect of the spin-coupling studies conducted on this system is evidenced in the form of two bond couplings which are exhibited by the resonances which were ultimately assigned to C5, C7 and C10. In conjunction with the substantiation for these assignments provided from the spin lattice relaxation experiments, this behavior may serve as a useful assignment criterion in the discrimination of isomers expected to be encountered if the elaboration of the pyrrole ring were conducted on appropriately substituted phenothiazines such as 2-chlorophenothiazine.

Continuing from the partial assignment of the  $^{13}\text{C}$ -nmr spectrum of **1**, which was obtained from the decoupled and proton-coupled spectra, relaxation studies were undertaken in an effort to obtain a complete and unequivocal assignment of the entire spectrum of **1**. The relaxation experiments conducted comprised two distinct groups: progressive saturation (30) experiments which were intended to provide information on the relaxation of the nonprotonated carbons to facilitate the assignment of C2a, C2b and C10a; inversion-recovery (31,32) experiments which were intended to probe the molecule for the possible existence of an axis of anisotropic reorientation which could be used as a further discriminatory criterion for the protonated resonances comprised by C2, C4, C7, C8, C9 and C10.

Relaxation times for the non-protonated carbons of **1** were determined using the progressive saturation technique (30) which, although somewhat less accurate than the

inversion-recovery technique (33) has the advantage of consuming significantly less instrument time. An additional precaution which was taken prior to the execution of these experiments was the degassing of the sample with zero grade argon to remove any dissolved oxygen which would have the effect of foreshortening of the observed relaxation times.

Non-protonated carbon relaxation times for **1** are shown in Table II. From the outset, it was assumed that the relaxation times obtained for C5a, C7a and C10a would be more-or-less equivalent while the relaxation time for C2a would be somewhat shorter and the relaxation time for C2b somewhat longer (34). The particular advantage of this facet of the assignment was that the assigned resonances for C5a and C7a would serve as a model for the relaxation behavior of C10a thereby confirming the assignment of the latter. The assignment of C2a, which has the most adjacent protons of any of the non-protonated carbons was expected to be the most efficient, based on equation 1, while the exact converse obtained for C2b which was further separated from adjacent protons than any of the other non-protonated resonances.

Assumptions for the relaxation behavior of the non-protonated carbon resonances were derived from calculation of the anticipated relaxation times using equation 1, in which:

$$1/T_1^{DD} = \hbar^2 \gamma_C^2 \gamma_H^2 r_{CH}^{-6} \tau_c \quad (1)$$

where  $\hbar^2$  is Planck's constant,  $\gamma_C^2$  and  $\gamma_H^2$  are the gyromagnetic ratios of carbon and proton respectively,  $r_{CH}^{-6}$  is the distance between the  $^{13}\text{C}$  nucleus in question and all participating protons and  $\tau_c$  is the reorientational correlation time which was derived from inversion-recovery experiments discussed below. In addition, a further important contributor to the relaxation of  $^{13}\text{C}$ -resonances where there is no proton located within 2.0 Å is the  $^{14}\text{N}$  -  $^{13}\text{C}$  dipolar relaxation mechanism which would be operable for C2b and C10a. Contributions to relaxation by this mechanism were taken into account using the method of Norton and Allerhand (35) in which the relaxation of the  $^{13}\text{C}$ -nucleus by interaction with the dipolar nucleus, j, is given by equation 2,

$$1/T_{ij} = (2/15) \hbar^2 \gamma_C^2 \gamma_j^2 S_j (S_j + 1) r_{Cj}^{-6} \chi_j \quad (2)$$

where  $S_j$  is the spin-quantum number of nucleus j,  $\gamma_C$  and  $\gamma_j$  are the gyromagnetic ratios of the  $^{13}\text{C}$  and j nuclei respectively,  $r_{Cj}^{-6}$  is the interatomic distance between  $^{13}\text{C}$  and j and where the term  $\chi_j$  is defined by equation 3 where

$$\chi_j = \frac{\tau_R}{1 + (\omega_j - \omega_C)^2 \tau_R^2} + \frac{3\tau_R}{\omega_C^2 \tau_R^2} + \frac{6\tau_R}{1 + (\omega_j + \omega_C)^2 \tau_R^2} \quad (3)$$

Based on this set of expressions, the calculated relaxation times for the non-protonated carbons shown in Table II were obtained, which are seen to be in reasonably good accord with the experimentally determined values.

Relaxation times for the protonated carbons of **1**, shown in Table III, were determined to obtain the reorientational correlation time,  $\tau_c$ , and in an effort to obtain additional information about the molecule to permit the assignment of the remaining protonated carbons which were as yet unassigned. Levy and co-workers (36,37) have shown that a relatively diverse group of substituted benzenoid systems reorient in an anisotropic fashion about the symmetry axis of the system. In the case of the pyrrolo[3,2,1-*k*]phenothiazine system (**1**), while there was not a defined symmetry axis, it was assumed that the system would reorient about an axis which would roughly pass through the center of the phenothiazine system. Assuming that the axis passes simply through the system such that C-H bond vectors assume angles of  $\sim 30^\circ$  and  $\sim 90^\circ$ , (38) the carbon atoms related to these particular angular dependencies would be expected to undergo differential relaxation as a result of the angular dependence of the relaxation expressions.

Using the  $30^\circ/90^\circ$  angular dependence ascribed to this model of relaxation behavior, anticipated  $T_1$  relaxation ratios can be determined by solving equation 4 (39) for various values of the tumbling preference ratio,  $\rho$ , with two simultaneous values for  $\chi$ . Graphical representation of the solution of this expression is shown in Figure 4 which can be used as an empirical estimator of the tumbling

$$\chi\theta = \frac{1}{4} (3\cos^2\theta - 1)^2 + 18(5 + \rho) \sin^2\theta \cos^2\theta + \frac{\rho}{4} (1 + 2\rho)^{-1} \sin^4\theta \quad (4)$$

preference ratio without resorting to using the exact expression (40). It should further be noted that the tumbling preference ratios which result from this type of solution, while useful for qualitative applications, they cannot be used quantitatively. This condition arises since slight deviations from the precise angles used for the generation of the relationship shown in Figure 4 will produce similar curves which cannot easily be discriminated from the ideal system as a result of the relative degree of accuracy of  $T_1$  measurements and the lack of a symmetry operator defined axis. To illustrate the slight differences arising by only small angular deviations from the  $30^\circ/90^\circ$  angular dependence, a related family of curves relating  $T_1$  ratios to the tumbling preference ratio are shown in Figure 5.

Examination of the relaxation data from the protonated carbons, shown in Table III, illustrates a small difference ( $\sim 20\%$ ) between the carbons with pseudo-coincident C-H bond vectors (average  $T_1 = 1.07 \pm 0.03$  seconds) and the carbons bearing noncoincident C-H bond vectors (average  $T_1 = 1.27 \pm 0.02$  seconds) resulting in a  $T_1$  ratio = 1.19 which corresponds to an approximate tumbling preference ratio,  $\rho = 1.6$ . Assignment of the remaining protonated resonances was thus achieved using this observation in conjunction with the observed  $^{13}\text{C}$ -nmr chemical shifts of phenothiazine (**4**) (20) and the spin-coupling constants discussed above. These assignments are shown in Tables I

and III

In conclusion, it is appropriate to compare the assigned  $^{13}\text{C}$ -nmr chemical shifts of **1** with the phenothiazine (**4**) (20) and indole (**3**) (19) model compounds used as an adjunct in this assignment. On this basis, relative to phenothiazine, the pyrrolo[3,2,1-*k*]phenothiazine ring system exhibits profound changes in the chemical shifts of the portion of the molecule bearing the attachment of the pyrrole ring as shown in Figure 6. Not surprisingly, these changes are greatest at the positions which would experience alterations in electron density as a result of extended conjugation provided by the additional ring fused to the phenothiazine nucleus. In contrast, with the exception of the resonance for C10a, the unsubstituted portion of the molecule reflects only minor changes in chemical shift. Perhaps more surprising, however, is the good agreement obtained when rings A and D of the pyrrolophenothiazine system are compared with indole (**3**). On this basis, a substantially better agreement is obtained between the observed  $^{13}\text{C}$ -nmr chemical shifts of the pyrrolophenothiazine and the indole model compound. It is logical to assume that additional studies in which other systems, for example piperidine to give the piperidinophenothiazine, could best be modeled by using a combined model derived from phenothiazine and the appropriate bicyclic system.



#### EXPERIMENTAL

Pyrrolo[3,2,1-*k*]phenothiazine was prepared as previously described (13). All  $^{13}\text{C}$ -nmr experiments were performed on a Varian XL-100-15 nmr spectrometer system operating in the Fourier transform mode at 25.158 MHz. The spectrometer was equipped with a Nicolet Technology Corporation Model TT-100 data system, an NT-440 frequency synthesizer and a TT-760 decoupler. Standard spectral parameters were as follows: pulse width 10  $\mu$ seconds ( $45^\circ$  flip angle); pulse delay 3.00 seconds; data size 4K for decoupled spectra and 8K for coupled spectra providing acquisition times of 0.8192 and 1.6384 seconds, respectively; sweep width 5 KHz; line broadening 1.0 Hz. Selective excitation experiments were performed using the modifications previously described (24). Relaxation experiments were performed on a sample of **1** comprised of 250 mg. dissolved in 3.0 ml. of deuteriochloroform and degassed with zero grade argon for 30 minutes and two freeze-pump-thaw cycles. All spectra were obtained at an ambient probe temperature of  $33^\circ$ . Progressive saturation experiments were conducted with a series of twelve tau values ranging from 2.0 to 256.0 seconds. Inversion recovery experiments were conducted using a series of fifteen tau values ranging from 250  $\mu$ seconds to 6.0 seconds with an interpulse delay of 10.0 seconds. Values for the  $90^\circ$  and  $180^\circ$  pulses used in these experiments were obtained by optimization of pulse width using a standard 60% dioxane in hexadeuteriobenzene reference sample.

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- (38) This angular relationship, which is not defined by a symmetry operator, provides a useful qualitative estimator of relaxation behavior allowing the discrimination between resonances which are pseudo-coincident ( $\sim 30^\circ$ ) from those which are non-coincident ( $\sim 90^\circ$ ). Although approximate tumbling preference ratios can be obtained by this treatment, they should under no circumstances be used as quantitative information since this may lead to severe interpretational errors as a result of the only approximately defined reorientational axis.
- (39) Equation 4 appears in the form presented in this manuscript in the early work of A. Allerhand, D. Dodrell and R. Komoroski, *J. Chem. Phys.*, **55**, 189 (1971) although these authors did not utilize the expression in this capacity. The first application of this expression in the determination of differences in T<sub>1</sub> relaxation times as a result of anisotropic reorientation was described in references 36 and 37.
- (40) A more precise determination of the axis of anisotropic reorientation can be obtained by treating the data according to the method of Platzer (*cf.* reference 17). In this fashion, a quantitative treatment of the data would be possible based on the exact angular dependencies of the data. In the case of the example at hand, this type of rigorous treatment would appear to be warranted only in the case of several substituted compounds which would then allow the evaluation of the effects of the substitution on the overall anisotropic reorientation of the molecule.