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Restricted Rotation Involving the Tetrahedral Carbon. XXVI. Certainties and Uncertainties Involved in the Rates of Exchange among Three Sites as Obtained by Total Line Shape Analyses of ^{1}H NMR Spectra: The Case of Methylene Signals[1]

Michinori Ōki,* Motomichi Kono, Hiroshi Kihara, and Nobuo Nakamura
Department of Chemistry, Faculty of Science, The University of Tokyo, Tokyo 113

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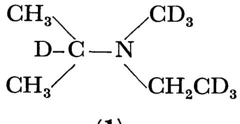
Benzyl methylene signals, which split into an AB quartet and a singlet and show temperature dependence, are obtained at various temperatures and are simulated with the use of two independent rates of rotation. Certain limitations of accuracy are found in this method. The uncertainty becomes less if additional data are provided from other sources, but never becomes negligible. Contribution of the slower process is found difficult to detect especially when the population involved in the process are the less.

The total line shape analysis of the NMR spectra is becoming increasingly popular due to the widespread utilization of high-speed computers and availability of the computing program.[2] The method furnishes the rate constants of 10^{-1}—10^{5} s^{-1} easily and the data are favorably compared[3] with those obtained by other methods, when the exchanging sites are two, although there is a warning that the entropy of activation thus obtained may include a considerable error.[4]

As to the exchanging sites of more than two, there are some scattered reports which claim the rates of different processes are separately obtained. A typical example is a combination of internal rotation about the C–N bond and inversion with respect to the nitrogen atom of amines. Bushweller *et al.* succeeded in separating the two processes in a deuterated *N*-ethyl-*N*-methylisopropylamine (**1**) and obtained the rates of the respective process.[5] This method takes advantage of the fact that the rates of the two processes are so much different that the coalescence phenomena are found at two temperatures. The classical example of the carbon skeleton in this type of exchange was reported by Kessler *et al.* on *cis*-1,2-di-*t*-butylcyclohexane (**2**) in which rotation about the C_1–C_2 bond and ring inversion are observed at different temperatures.[6] A recent report by Anet and coworkers[7] on a 1,2-cyclononadiene (**3**) also falls into this category.



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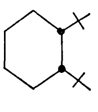

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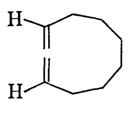

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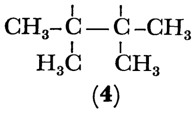
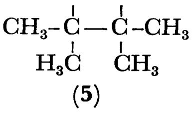


$$CH_3-\overset{H}{\underset{H_3C}{C}}-\overset{H}{\underset{CH_3}{C}}-CH_3$$

(**4**)



$$CH_3-\overset{X}{\underset{H_3C}{C}}-\overset{Y}{\underset{CH_3}{C}}-CH_3$$

(**5**)

Reports from this laboratory made use of the fact that *d* and *l* isomers are not distinguishable by ^{1}H NMR spectroscopy and treated many ethane derivatives, as if there were only two sites exchanging, although there are actually three sites.[8a] The use of ^{13}C NMR in the rate analysis of internal rotation[8b] also falls in this category. This type of treatment seems to be convenient when one barrier is high relative to others. Thus Lunazzi *et al.* treated the ^{13}C NMR spectra of 2,3-dimethylbutane (**4**) in this manner and good agreement between the observed and the calculated spectra was obtained.[9] By *ab initio* calculation barrier to gauche-to-gauche transformation is found to be *ca.* 8 kcal/mol, whereas the line shape analysis (4.3 kcal/mol) and *ab initio* calculation (4.6 kcal/mol) afforded barriers to gauche-to-trans transformation which are in good accordance. Bushweller *et al.* performed also total line shape analysis on 2,3-dimethylbutane derivatives (**5**) by assuming that the gauche-to-gauche barrier is high and the agreement between the observed and the calculated spectra was good.[10] The rotation of gauche-to-gauche seems to contribute little to the whole process.

The above cited cases are not general, of course. In the rotamer exchange, the barriers to rotation of gauche-to-gauche and gauche-to-trans are in general close to each other. Namely two processes of rotation compete in the general case. Then a question arises: to what extent can we rely upon the total line shape analysis in obtaining rate data when more than two independent processes are competing? To answer this question we have analyzed the line shape of benzyl methylene protons of 9-benzyltriptycenes (**6**) which exist as a mixture of *meso*, *d*, and *l* isomers, by taking all the processes

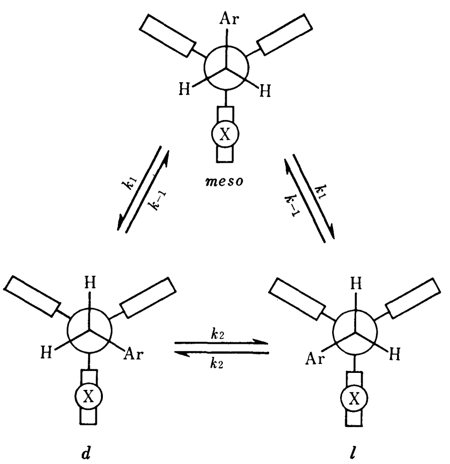
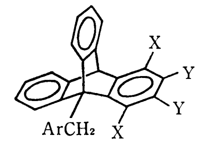


Fig. 1. Exchanging conformers and exchange processes.



(**6**)

into consideration. In this case three back-and-forth processes are possible, but, due to the presence of a pair of enantiomers, the number of rate constants converges to three: k_1, k_{-1}, and k_2, as shown in Fig. 1.

In this paper we describe the results of the total line shape analysis and discuss uncertainties associated with the calculation.

Experimental and Data Processing

Materials. The syntheses of 9-arylmethyl-1,4-dimethoxytriptycene and 9-(*p*-chlorobenzyl)-1,2,3,4-tetrachlorotriptycene used in this study have been reported elsewhere.[1,11]

Measurement. The spectral measurement was performed on a JEOL FX 60 spectrometer equipped with FT facilities. The conditions of the measurements were the same as described in a previous paper.[1]

Total Line Shape Analysis. The benzyl methylene signals consisted of an AB quartet and a singlet due to the *dl* and the *meso* forms, respectively. The system was treated as the exchange of AB-BA-C_2 by the modified Binsch program.[12] The chemical shift difference and the coupling constant are used as observed. T_2 was calculated from the line width of TMS added as an internal standard. Population ratios derived in the previous paper were used for the calculation except for 9-(*p*-chlorobenzyl)-1,2,3,4-tetrachlorotriptycene, with which determination of the population ratio was straightforward because clear AB quartet and C_2 signals were observed owing to the absence of the methoxyl signals which prevented the accurate determination in the other compounds. Other pertinent considerations are described in the previous paper.

Results and Discussion

General Consideration. As a starting point, we discuss the limitation of the usefulness of the total line shape analysis. Shown in Fig. 2 are the computed spectra of various relative rates of the two processes using the chemical shift differences and the coupling constant of 9-benzyl-1,4-dimethoxytriptycene. The variables are limited to two because k_1 and k_{-1} are related by the equilibrium constant: $K(dl/meso)=2k_1/k_{-1}$. In our cases the population ratios are available from the integrated intensities and/or the chemical shifts as discussed in the previous paper.[1] We stick to the two independent variables because, although it is possible to obtain k_1 and k_{-1} independently in the computation of the spectra, increasing the number of the variables will increase the uncertainty in the obtained data. The used parameters were as follows: $\Delta\nu_{AB}$ 38.33 Hz, $\Delta\nu_{AC}$ 3.395 Hz, J_{AB} 17.46 Hz, T_2 0.318 s, molar fractions of the *meso* and the *d* (or *l*) forms 0.22 and 0.39, respectively.

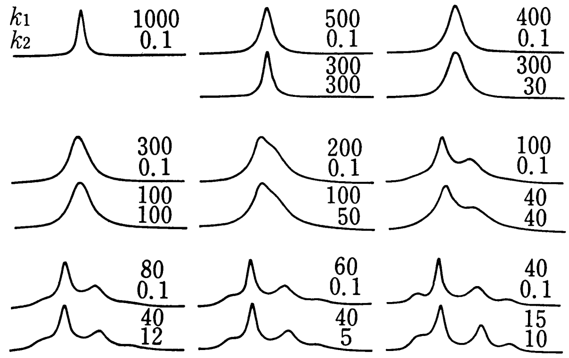
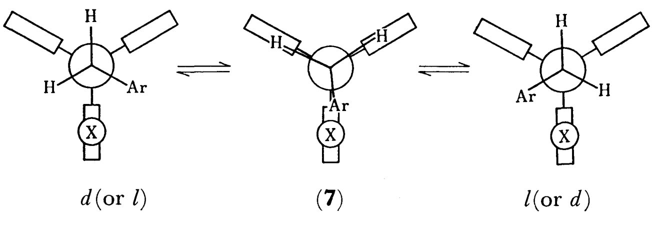


Fig. 2. Computed spectra with the use of various k_1's and k_2's taking other necessary data from those of 9-benzyl-1,4-dimethoxytriptycene.

In the rows 1, 3, and 5, are shown the line shapes computed with a constant k_2 of 0.1 s^{-1} and various k_1's from 1000 s^{-1} to 40 s^{-1}. The line shapes seem to be determined by the main process at the level of this slow process, because changing the k_2's to 0.01 s^{-1}, while using the k_1's of the same range as above, did not produce any significant change. It may be concluded that a process, the rate constant of which is less than 1/100 of that of a main process has no effect on the line shape of the NMR spectra.

In the rows 2, 4, and 6, are shown the line shapes computed using relatively large k_2 values. As is seen from the simpler spectra, it is clear that a unique combination of two rates cannot be obtained if the spectral shape is simple (compare for example, the shape of $k_1=300$ and $k_2=0.1$ s^{-1} with that of $k_1=100$ and $k_2=100$). Thus we may better exclude one-peaked spectra from the calculation as was pointed out previously.[3] In sharp contrast, the computed spectra with a constant k_2 of 0.1 s^{-1} can differentiate the k_1's of 80, 60, and 40 s^{-1} as shown in the row 5 and the rate of a slow process may be reflected if it becomes 1/10 of that of a fast process as is shown in the bottom row. It seems that, if the spectra are complex, there is a possibility that the rates of the two processes are uniquely determined by this method. Thus we will discuss the line shapes of considerable complexity in the following text to make the discussion more reliable. Another point worthy of note is that, if we neglect a process which does exist, the apparent rate constant of the main process is obtained larger than the real: if k_2 is practically neglected by putting the value of 0.1, the top right curve is simulated by using k_1 of 400 s^{-1}, whereas the curve may actually correspond to k_1 and k_2 of 300 and 30 s^{-1}, respectively (second from top, right curve). Therefore we should take the rate constant as a maximum value even though the main process could explain the line shape completely and the minor process is negligible.

If we assume that the transition state of rotation is a fully eclipsed form, the transition state of the highest energy is the one (**7**) in which the aryl group eclipses



d(or *l*) (**7**) *l*(or *d*)

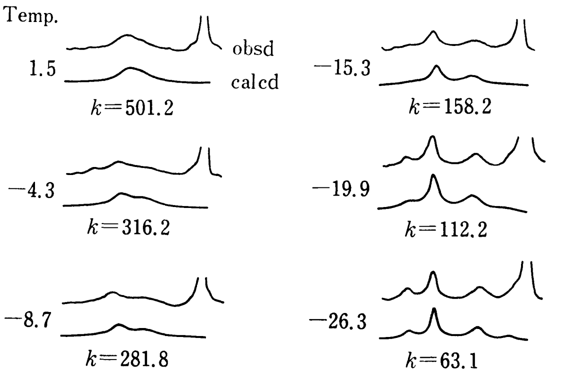


Fig. 3. Observed and calculated spectra of the methylene region of 9-(p-chlorobenzyl)-1,4-dimethoxytriptycene at various temperatures. The strong signal at the higher field corresponds to the methoxyl signal and is neglected in the computation.

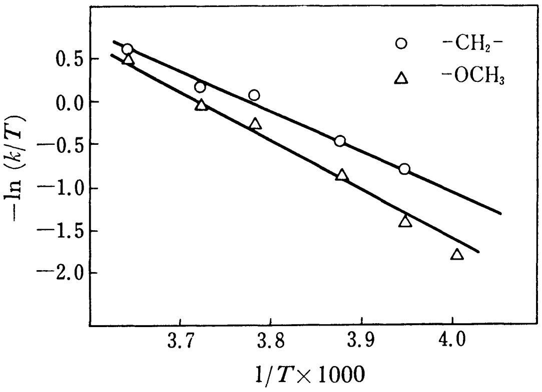


Fig. 4. Comparison of the Eyring's plots using k_1's obtained by the analysis of the methylene part and the methoxyl signals of 9-(p-chlorobenzyl)-1,4-dimethoxytriptycene.

the peri substituent. This transition state is realized when the rotation occurs from a d form to an l form or *vice versa* but never appears in the process of $meso\rightarrow d$ (or l). Therefore we can reasonably assume that k_1 and k_{-1} are larger than k_2.

Since the line shapes are affected by fast processes to a greater extent than slower processes, we may be able to obtain fairly good agreement between the real and the calculated rates which are obtained by neglecting the $d\rightleftharpoons l$ process. Fig. 3 shows the observed spectra at the methylene and methoxyl region of 9-(p-chlorobenzyl)-1,4-dimethoxytriptycene at various temperatures and the computed spectra which were obtained by neglecting the $d\rightleftharpoons l$ process and the methoxyl signal and were considered the best fit. The used parameters for computation were differences in chemical shifts of $\Delta\nu_{AB}$—40.52 Hz and $\Delta\nu_{AC}$ 2.148 Hz, coupling constant of 17.4 Hz, and T_2's and populations$^{1)}$ at the respective temperatures. Fig. 4 shows the Eyring's plot using the rate constants thus obtained and compares the result with the straight line corresponding to the $meso\rightleftharpoons d$ (or l) process as obtained by the total line shape analysis of the methoxyl singnals.$^{1)}$ Apparently this treatment gives higher rate values and a lower $\Delta H^{\ddagger}$, the difference amounting over 3 times of the standard deviation. Thus the results indicate that we should not overlook the process $d\rightleftharpoons l$, although the rate may be small.

Aquisition of Two Independent Rate Constants by Calculation. We tried to evaluate the best k_1 and k_2 of the 9-(chlorobenzyl)-1,4-dimethoxytriptycene by using the computation only. For each spectrum, population ratio at that temperature, coupling constant, differences in chemical shifts, and T_2 are put as constants and k_1 and k_2 as variables. The rate constants are roughly changed by the scale of log e for the convenience of computation and an array of line shapes is made. From

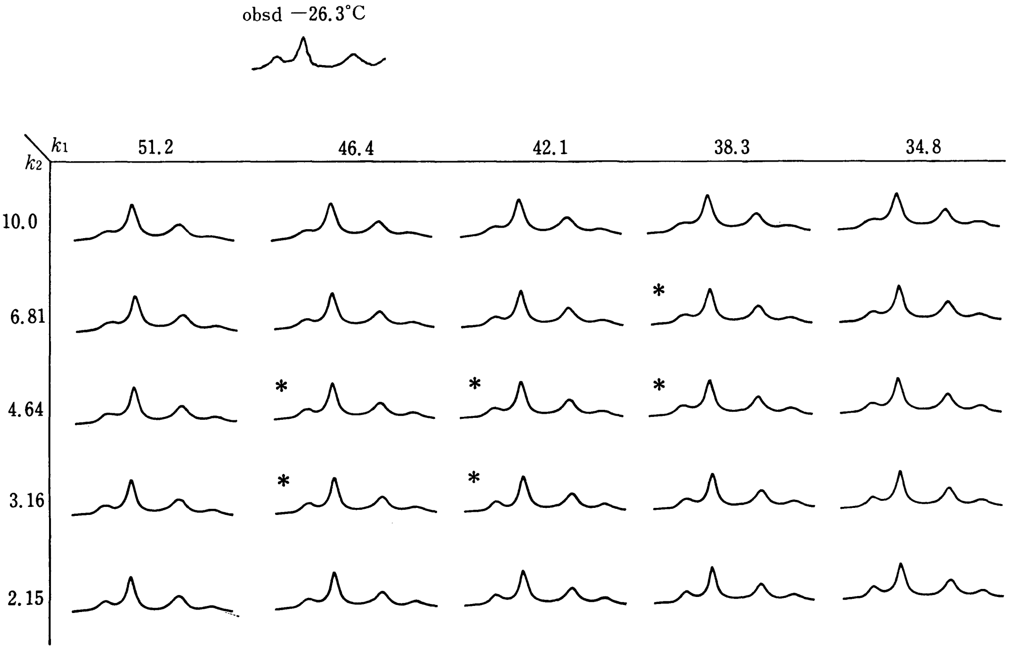


Fig. 5. Computed line shapes with various k_1's and k_2's using the data of p-(chlorobenzyl)-1,4-dimethoxytriptycene at −26.3 °C. Those marked with stars are the best fit spectra.

the array a seemingly best fit region is picked up and the portion is expanded with small variations in k_1 and k_2 to make a finer array. An example is shown in Fig. 5, taking the spectrum at −26.3 °C. By visual fitting, we cannot specify a single computed spectrum but can pick up 6 spectra which fit best. Thus it is possible to obtain k_1 and k_2 with certain ranges. Similarly at other temperatures, sets of 2 to 6 best fit spectra are obtained. The results are shown in Table 1.

Table 1. Rate constants obtained by the visual fitting of the computed spectra with the observed for 9-(*p*-chlorobenzyl)-1,4-dimethoxytriptycene at various temperatures

Temperature (°C)	Rate constants (s^{-1})	
	k_1	k_2
−15.3	110—90.9	14.7—6.81
−19.9	75.0—48.6	14.7—4.64
−26.3	46.4—38.3	6.81—3.16
−31.1	21.5−19.6	6.81—4.64
−37.3	16.2—13.3	3.16−1.47

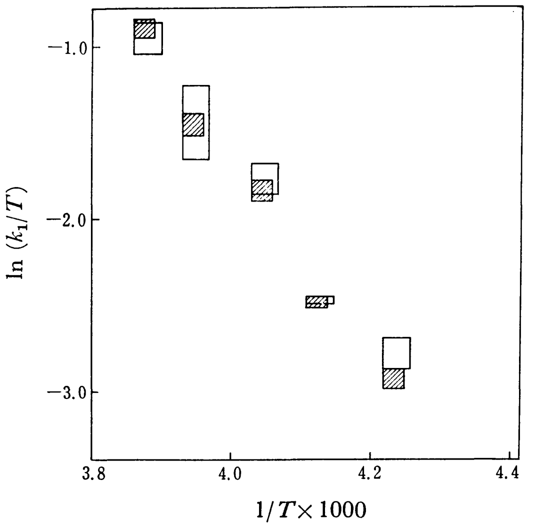


Fig. 6. Eyring's plot showing the ranges of possible errors for the process *meso*→*d*(or *l*) of 9-(*p*-chlorobenzyl)-1,4-dimethoxytriptycene. Open rectangles correspond to those obtained by computation only and hatched rectangles to those derived by the methoxyl signals, the temperature ranges of the latter being changed slightly for the convenience of comparison.

Figure 6 illustrates an Eyring's plot pertaining to the rate constants k_1 with probable error ranges indicated by the widths in the ordinate direction. The widths in the direction of abscissa is written by taking the error of temperature reading, which is ±0.6 °C, into consideration. Similarly Fig. 7 shows an Eyring's plot pertaining to the rate constants k_2. Although it is possible to obtain $\Delta H^{\neq}$ and $\Delta S^{\neq}$ as 10.2±0.6 kcal/mol and −9.6±2.3 e.u., respectively, for the process *meso*→*d* (or *l*) with a percent error of 5.6, it may contain errors derived by the ambiguity in the k_1's. It is difficult to draw a straight line in the case of k_2's.

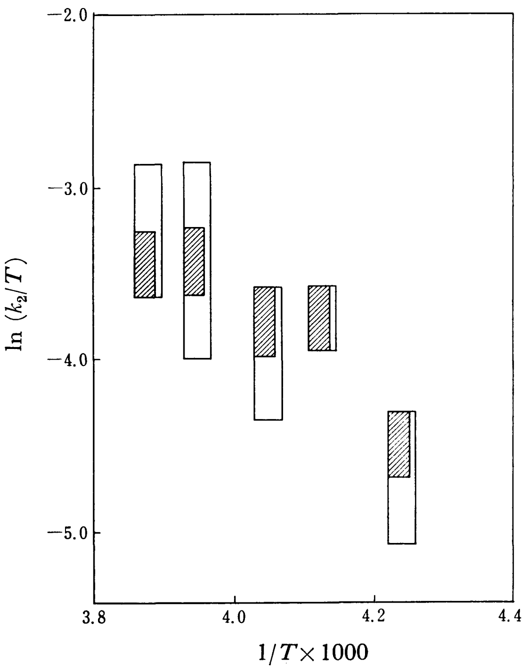


Fig. 7. Eyring's plot showing the ranges of possible errors for the process $d\rightleftharpoons l$ of 9-(*p*-chlorobenzyl)-1,4-dimethoxytriptycene. Open rectangles correspond to those obtained by computation only and hatched rectangles to those derived by using k_1's obtained from the methoxyl signals. For the temperature ranges of the latter, see the caption of Fig. 6.

Barrier to the Minor Process. As pointed out in the previous paper, the rate constants k_1 may be obtained by analyzing the line shapes of the methoxyl signals. One may hope then that if we put these data to obtain the best fit spectra, we should be able to obtain k_2's of better quality. Indeed, the rate constants were obtained as follows at the temperatures where we have the methylene data, using the methoxyl signal shapes (units are s^{-1}): 106 (−15.3 °C), 59.5 (−19.9 °C), 39.8 (−26.3 °C), 19.9 (−31.1 °C), 12.6 (−37.3 °C). These data are also shown in Fig. 6, taking the error limit as ±5%, because we selected the best fit spectra by comparing the computed spectra of *ca.* 5% intervals of rates. The ranges of the k_2's can then be reduced and are shown in Fig. 7. Apparently the linear relation may not be claimed: although we can treat the data by the least squares method to draw a straight line, its percent error amounts to 20.7. Thus it is not practical to obtain the kinetic parameters for the $d\rightleftharpoons l$ process from these data.

It is noteworthy, however, that the calculated spectra suggest that k_2 is close to 1/10—2/10 of k_1. This corresponds to the difference of *ca.* 1 kcal/mol in the barriers to the two processes. Therefore we conclude that the $d\rightleftharpoons l$ process possesses a higher barrier to rotation than the *meso*→*d* (or *l*) process by *ca.* 1 kcal/mol.

The Case of 9-Benzyl-1,2,3,4-tetrachlorotriptycene. This compound is picked up as a model because it poses another problem: does lesser population have any influence on determing a rate constant? Variation of the temperature influenced the spectra of the methylene

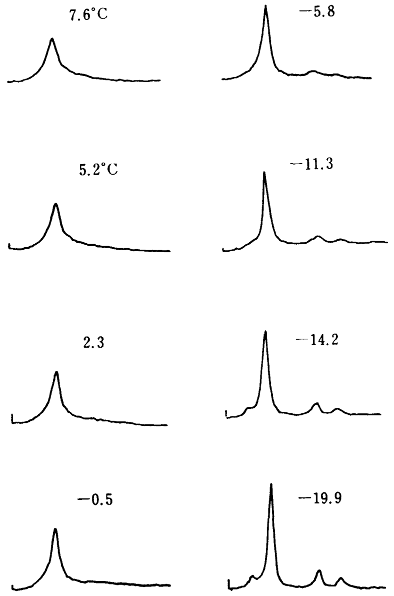


Fig. 8. Temperature dependent spectra of the methylene region of 9-benzyl-1,2,3,4-tetrachlorotriptycene.

Table 2. Populations of the *meso* and the *dl* forms and equilibrium constants of 9-benzyl-1,2,3,4-tetrachlorotriptycene at various temperatures

Temperature (°C)	Populations		*K*
	meso	*d* (or *l*)	(*dl*/*meso*)
7.6	0.63	0.18	0.58
5.2	0.62	0.19	0.59
2.3	0.62	0.19	0.61
−0.5	0.61	0.19	0.63
−5.8	0.60	0.20	0.66
−11.3	0.59	0.21	0.70
−14.2	0.58	0.21	0.73
−19.9	0.56	0.22	0.78

part as shown in Fig. 8. The population was *ca.* 6 to 4 (*meso*: *dl*). The temperature dependence of the population ratios was determined as shown in Table 2 and the thermodynamic parameters were obtained as follows: ΔH -2.3 ± 0.3 kcal/mol, ΔS -9.8 ± 1.4 e.u. Therefore this compound is a model which possesses less populations of which exchange corresponds to the slow process.

Typical calculated spectra are shown in Fig. 9, where the spectrum at −14.2 °C is taken as an example. Parameters used for the calculation were as follows: $\Delta\nu_{AB}$ -52.29 Hz; $\Delta\nu_{AC}$ 4.095 Hz; J_{AB} 18.6 Hz; populations, *meso* 0.58 and *d* (or *l*) 0.21. T_2's were observed at respective temperatures. As is seen in the figure, it is hardly possible to detect the effect of the slower process, although the rate constant was changed by a factor of almost 50. Thus we may be able to specify the rate constant of the faster process but not the slower one in this case: the line shapes are controlled by the faster process almost exclusively. We may obtain the rates of exchange *meso*$\rightleftarrows$*d* (or *l*) independently by looking at the ^{13}C NMR line shape but the rates thus obtained do not help in obtaining the rates of the slower process.

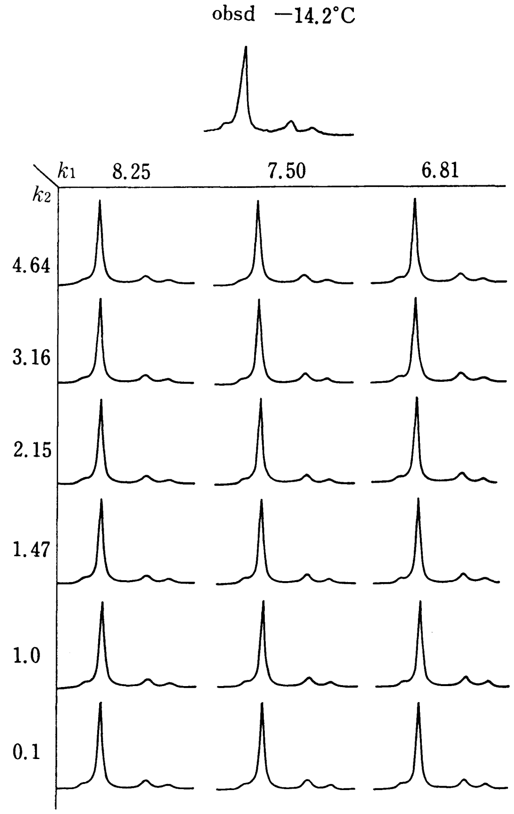


Fig. 9. Computed spectra of 9-benzyl-1,2,3,4-tetrachlorotriptycene at −14.2 °C using various k_1's and k_2's.

The rate constants k_1's were obtained as follows (given in s^{-1}): 56.2 (7.6 °C), 46.4 (5.2 °C), 42.1 (2.3 °C), 26.1 (−0.5 °C), 14.7 (−5.8 °C), 12.1 (−11.3 °C), 7.50 (−14.2 °C), 4.64 (−19.9 °C). The Eyring's plot using these values affords $\Delta H^{\neq}$ 12.5 ± 0.3 kcal/mol and $\Delta S^{\neq}$ -6.0 ± 1.3 e.u. for the *meso*→*d* (or *l*) process. The activation parameters for the reverse process *d* (or *l*)→*meso* are then $\Delta H^{\neq}$ 14.0 ± 0.3 kcal/mol and $\Delta S^{\neq}$ 2.0 ± 0.2 e.u. We may have to expect that these values contain errors as large as 10% in addition to that of the least squares treatment.

Conclusion

We conclude that, in 9-benzyltriptycenes possessing a substituent in one of the peri positions which are close to the substituent, the barrier to rotation is *ca.* 13 kcal/mol. The activation parameters may be obtained by treating the rate constants obtained by the total line shape analysis of the methylene part in ^1H NMR spectra. However, the following should be kept in mind in discussing the data.

1) The process with a large rate constant plays a decisive role in determining the line shape, as was pointed out by Bushweller *et al.*[10] and the rate of the slow process, if obtained, includes a larger error.

2) If the rate constant of a slower process is less than a hundredth of that of a faster process, the former

cannot be detected by the visual fitting of calculated spectra with the obersved. The difference in free energies of activation for the two processes must be smaller than 2—3 kcal/mol to be detected.

3) It is extremely difficult to obtain accurate data for a slow process by comparison of the observed and the calculated spectra. Neglect of the slow process results in overestimation of a fast process, the enthalpy of activation of which is obtained smaller than the true.

4) The populations in the exchange sites have influence on the detectability of a slow process. The exchange between two sites with fewer populations contribute to the line shape too little to affect, if the rate is small.

5) The ambiguity in determining the rates of two exchanging processes is reduced to some extent by utilization of information obtained by other means. However, it was not possible to erase all the ambiguities in the present case.

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