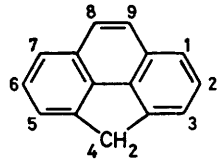
Electrophilic Aromatic Substitution. Part 29.[1] Protiodetritiation of 4*H*-Cyclopenta[*def*]phenanthrene: the Substituent Activation Factor A_f

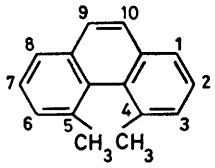
By **William J. Archer** and **Roger Taylor,*** School of Molecular Sciences, University of Sussex, Brighton BN1 9QJ

Rate coefficients have been determined for detritiation of each position of 4*H*-cyclopenta[*def*]phenanthrene (I) in trifluoroacetic acid at 70 °C, leading to the following partial rate factors (positions in parentheses): 27 050 (1), 5 680 (2), 14 000 (3), and 6 950 (8); the corresponding σ^+ values are −0.5065, −0.43, −0.475, and −0.44. The reactivity of (I) shows a combination of the properties of fluorene and phenanthrene, from each of which it is derived, and the relative positional reactivities are correctly predicted by Hückel localization energies. The σ^+ values predict accurately the isomer distribution in nitration (in acetic anhydride), but rather less satisfactorily the distributions in acetylation and molecular bromination due to the high polarizability of (I) which may be due in part to strain. Strain reduces steric hindrance at the 1- and 8-positions of (I) compared with the corresponding positions in phenanthrene. The reactivity of the 8-position of planar (I) is substantially less than that of the corresponding 9-position of non-planar 4,5-dimethylphenanthrene, supporting the view that the high reactivity of the latter derives from loss of ground-state conjugation. The effect of the methylene substituent in (I) compared with the methyl substituent in benzene and naphthalene demonstrates the over-riding importance of bond fixation in polycyclic aromatics; these substituent effects are predicted by easily calculated substituent activation factors (A_f).

Our interest in the reactivity of 4*H*-cyclopenta[*def*]-phenanthrene (I) has been stimulated by its relationship to 4,5-dimethylphenanthrene (II), the high reactivity of which we have attributed to ground state destabilisation produced by non-planarity,[2] and by reports of its nitration,[3] bromination,[4] and acetylation.[5] Through the generosity of Professor Yoshida in providing us with pure samples of each of the bromo-isomers of (I) we are able to describe the quantitative electrophilic reactivity of this strained planar aromatic in acid-catalysed hydrogen exchange, and therefore free from any steric effects. The information gained should further our understanding of polycyclic aromatic reactivity, a factor important for assessing the cause of carcinogenic behaviour of certain of these hydrocarbons.



(I)



(II)

RESULTS AND DISCUSSION

From the rate coefficients given in the Experimental section, and the exchange-rate coefficient for benzene under the same conditions,[6] the partial rate factors were obtained as shown in Figure 1. This shows also the partial rate factors for exchange in the related phenanthrene,[7] fluorene,[8] and 4,5-dimethylphenanthrene.[2] Notable features are as follows.

(i) The reactivity of the 8-position of planar (I) is almost six times less than that of the comparable 9-position of non-planar 4,5-dimethylphenanthrene. Now a 4- and a 5-methyl substituent increase the rate of exchange at the 9-position of phenanthrene by factors of 2.96 and 2.36, respectively.[9] A methylene substituent at both positions should therefore have two-thirds of the product of the overall effect, *i.e.* a factor of 4.6, so the predicted partial rate factor for the 8-position of (I) is 1 630 × 4.6 = 7 515. This is almost exactly the observed value so 4*H*-cyclopenta[*def*]phenanthrene shows

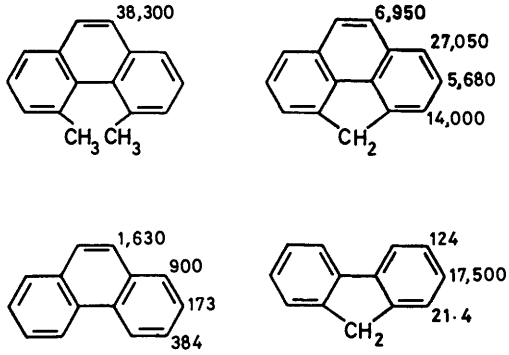


FIGURE 1 Partial rate factors for detritiation in anhydrous TFA at 70 °C

normal behaviour. However, the same calculation applied to 4,5-dimethylphenanthrene predicted a reactivity over three times smaller than that observed, attributed to non-planarity and consequent ground-state destabilization of the molecule;[2] the present results therefore reinforce that conclusion.

(ii) If the reactivity of (I) is compared with that of fluorene we obtain the effects of the pseudo-vinyl substituent (-CH=CH-) as shown in Figure 2. The results are

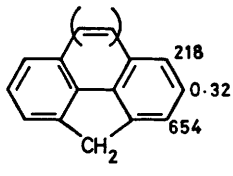


FIGURE 2 Effects of the pseudo-vinyl substituent upon the reactivity of fluorene

logical since the substituent is of the $-I$, $+M$ type so we expect *meta*-deactivation, and *ortho*-, *para*-activation in a reaction of fairly high resonance demand, such as

hydrogen exchange. The σ_m value for vinyl is 0.08 [10] and our results predict a value for -CH=CH- of 0.06, in excellent agreement. The σ^+_p value for vinyl is not known, but our results suggest a value of *ca.* −0.32 which is reasonable being more negative than σ_p (−0.08).[10]

A second point of note here is that the log f_o : log f_p value for the effect of the substituent is 0.83, in quite good agreement with the value of 0.86 generally obtained.[11]

(iii) If the reactivity of (I) is compared with that of phenanthrene we obtain the effects of the methylene substituent shown in Figure 3. Although the effect of

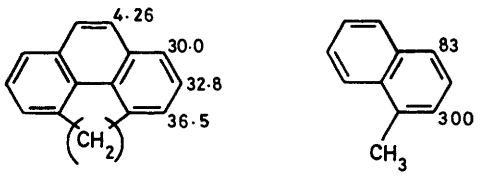
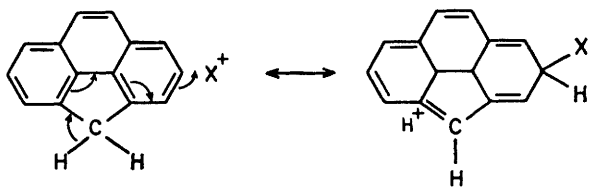


FIGURE 3 Effects of the methylene substituent on the reactivity of phenanthrene and of a methyl substituent on the reactivity of naphthalene

the *meta*-CH_2 substituent appears at first sight to be abnormally high, this arises only because it can conjugate with the 2-position (as it does in fluorene) as shown in (III).



(III)

In comparing the effects of the *p*-CH_3 and *p*-CH_2 substituents, two factors must be taken into account. (a) There are 5-positions for delocalization of the transition state charge in naphthalene, and 7-positions in (I). Thus the effect in the latter should be only 5/7 of that in the former. (b) The electronic effect of the CH_2 substituent should be only 2/3 that of the CH_3 substituent. Thus the predicted effect of the CH_2 substituent, based on the data for 1-methylnaphthalene, is $83 \times 5/7 \times 2/3 = 39.5$, reasonably close to that observed. Recently one of us combined the effects of bond fixation [9,12] and the differing numbers of sites for delocalization of charge in polycyclic aromatics into a substituent activation factor A_f [9] which predicts accurately the substituent effects in these molecules. In the present case the values of A_f across the 1,4-bonds in naphthalene and phenanthrene are 14.5 and 11.6, respectively; the smaller value for phenanthrene means that the substituent effect should be less, as observed.

The difference between the activation at the position *ortho* to the substituent in naphthalene and (I) is much more marked (Figure 3), and is not simply accounted therefore in terms of the different electronic effects of the two substituents and the different number of sites for delocalization. (This only gives a ' corrected ' value as calculated above of 143, much greater than the observed value of 35.5.) However, the A_f values correctly predict the observed result, being 18.2 and 13.4 for the *ortho*-interaction in naphthalene and phenanthrene, respectively. The difference is greater than between the values for the *para*-interactions above, predicting a greater difference in the substituent effect as observed. Moreover the corresponding *ortho* A_f value for benzene is 16.7, intermediate between the values for naphthalene and phenanthrene, as is the substituent effect. Lastly, the value for the *ortho*-interaction in phenanthrene is greater than for the *para*-interaction, and this also correctly predicts the observed substituent effect.

The A_f value is a function of bond fixation, itself related to bond order. We have calculated by the Hückel method, the bond orders for the 3,4-bond in phenanthrene (1.702) which may be compared with that for the 1,2-bond in naphthalene (1.725). These values therefore predict that the *ortho*-substituent effect should be smaller in phenanthrene. This should be even more true in (I) because the bridging by the methylene group will introduce strain and this should lengthen (and lower the bond order of) the bond which corresponds to the 3,4-bond in phenanthrene. Unfortunately it is not possible to obtain meaningful calculations in (I) itself because one has to regard the CH_2 substituent as carbon with a lone pair of electrons, which grossly exaggerates the degree of conjugation between the substituent and the aromatic rings.

(iv) From the partial rate factors, σ^+ values of −0.5065, −0.43, −0.475, and −0.44 are obtained for the 1-, 2-, 3-, and 8-positions, respectively. With these values and the appropriate ρ factors, the partial rate factors and hence isomer yields in nitration, acetylation, and molecular bromination may be calculated. These are given in Table 1 along with those obtained experimentally.[3-5] Nitration in acetic anhydride gives very good agreement with prediction whereas nitration in acetic acid is by contrast very anomalous. This is surprising since it is more usual for the former condition to produce a typical substitution patterns.*

The data for acetylation are particularly interesting because the isomer distribution for nitromethane as solvent gives a very good correlation with prediction, and this is rarely if ever observed with other aromatic compounds because of the high steric hindrance to acetylation. We therefore believe this correlation to be fortuitous, arising from a cancellation of two opposing factors *viz.* steric hindrance and polarizability. Our reasons are as follows.

(a) Acetylation in nitro-solvents is well known to be more sterically hindered than acetylation in chloroform.[13] This is clearly shown in Figure 4 which gives the isomer distributions for acetylation [14] and benzoylation [15] of phenanthrene in these two solvents. Although in phenanthrene the site most activated towards electrophilic substitution is the 9-position, followed by the 1-

* A referee has noted that nitrosation may be responsible since urea was not added to the nitric acid–acetic acid mixture.

TABLE 1

Predicted and observed isomer ratios for electrophilic substitution of 4*H*-cyclopenta[*def*]phenanthrene

	Nitration			Acetylation			Bromination	
		Observed			Observed			
Position	Predicted	Ac_2O	HOAc [a]	Predicted	$MeNO_2$	$CHCl_3$	Predicted	Observed
1	43	49	37	51	51	74	59	80
2	14	14	1	10	12	8	7	9
3	27	22	21	26	32	15	25	15
8	16	15	41	13	5	3	9	5

[a] Similar results were obtained using nitromethane as solvent.

position (the order is $9 > 1 > 4 > 3 > 2$ [7]), in acetylation in nitromethane these positions become the *least* reactive; changing to chloroform as solvent produces a dramatic increase in yields at these positions (about six-fold in each case). For benzoylation (a less hindered reaction [16]) the

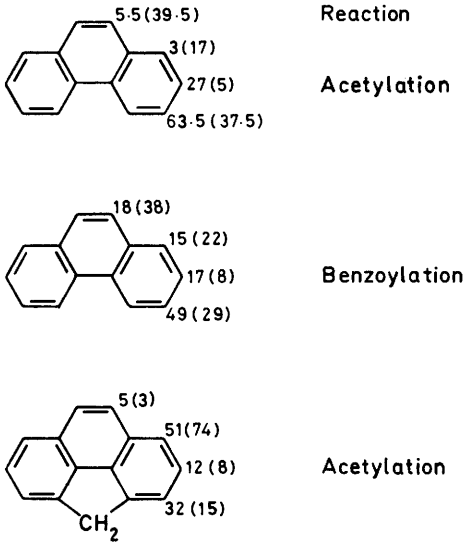


FIGURE 4 Isomer yields in acylation of phenanthrene and 4*H*-cyclopenta[*def*]phenanthrene in nitromethane and in chloroform (in parentheses)

yields of 1- and 9-isomers in nitromethane as solvent are rather greater, but also increase (and consequently by a smaller amount, about two-fold) on changing to chloroform as solvent.

(b) The comparable positions in (I) are, we believe, much less hindered because the bridging methylene introduces strain which must increase the distances between the *peri*-hydrogens on the other side of the molecule. Thus although acetylation of (I) in chloroform compared to nitromethane produces a similar pattern to that observed with phenanthrene,* the increase in the yield of the 1-isomer is much smaller, and it is probable that acetylation in chloroform is not sterically hindered at all, which would make (I) unique with regard to acetylation. If this is so, the reason why the isomer yields do not correspond to those predicted requires explanation, and we believe it is due to (I) being very polarizable especially with regard to its reactivity at the 1-position. Thus as the electrophile becomes less reactive and more selective there will be an increase in the proportion of the major (*i.e.* 1-) isomer over and above that which is a mathematical consequence of the Hammett equation [17] (itself evident from the predicted data in Table 2). This

TABLE 2

Hückel localization energies for electrophilic substitution

Compound	Position	$-\Delta E/\beta$	Partial rate factor for detritiation
4*H*-Cyclopenta[*def*]-phenanthrene	1	1.884	27 050
	2	2.415	5 680
	3	1.887	14 000
	8	2.201	6 950
Phenanthrene	1	2.318	900
	2	2.498	173
	3	2.454	385
	4	2.366	810
	9	2.299	1 630

explanation is another example of the reactivity–selectivity principle and its correctness is supported by the data for molecular bromination (Table 2) which shows the trend to be reinforced in this the reaction of highest ρ-factor. The polarizability of polycyclic aromatics is of course well known and examples have been noted previously.[18] For (I) the polarizability may be enhanced by strain which, by increasing the C–C bond

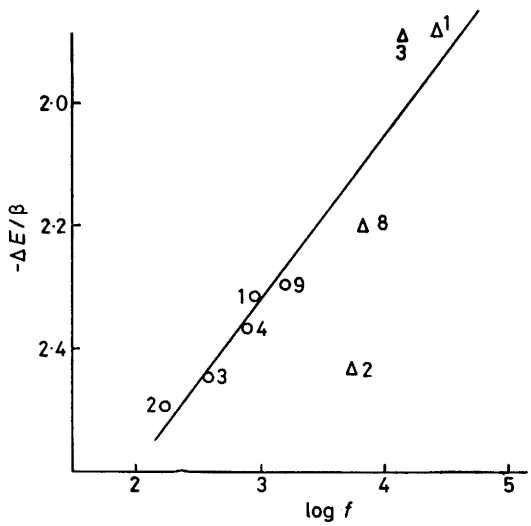


FIGURE 5 Correlation of logarithms of partial rate factors with localization energies for hydrogen exchange of phenanthrene and (I): △, positions in (I); ○, positions in phenanthrene

* The decrease in the yield of the 8-isomer is slightly anomalous, but may be due to a small error in determining the yield of the (most minor) product component.

lengths in the perimeter may result in less π-electron delocalization in the ground state so that these electrons are more polarizable under conditions of high demand.

Hückel localization energy calculations (Table 2) correctly predict the reactivity order in (I), though when taken along with the data for phenanthrene this can be seen to be rather fortuitous since the reactivity of the 2-position is underestimated by an order of magnitude (Figure 5). Hückel calculations are really only successful with pure polycyclics and are less able to cope with substituents such as the methylene group in (I). Thus the calculations fail completely with fluorene (the reactivity of the 2-position is underestimated even more) and it is significant that in fluorene there is a lower aromatic ring : substituent ratio.

EXPERIMENTAL

All the bromo-compounds were very kindly supplied by Professor M. Yoshida, Utsunomiya University, Japan, and their preparation has been described.[3,4] Each compound was converted into the tritiated derivative in the manner described below for the 8-isomer.

[8-^{3}H]-4H-*Cyclopenta*[def]*phenanthrene*.—A solution of 8-bromo-4*H*-cyclopenta[*def*]phenanthrene (0.005 g, 1.85×10^{-5}M) in dry tetrahydrofuran (0.5 ml) was added to a stirred solution of n-butyl-lithium (0.2 ml of 0.1M solution) in dry THF (0.5 ml) in a flask under dry nitrogen; the solution immediately turned deep red. After 1 min, tritiated water (1 drop of 100 mCi ml^{-1} activity) was added and the colour disappeared. The solution was stirred during a further 5 min and worked up in the usual way to give a semi-crystalline residue. G.l.c. analysis (5 ft × 6 mm i.d. column packed with 5% OV 101 absorbed onto 100—120 mesh Chromosorb G, operated at 230 °C) showed the presence of three peaks. One corresponded to unchanged starting material, one to the required product (shown by comparison with an inactive sample) and one unidentified peak [which was almost certainly an n-butyl derivative of (I)]. The residue, dissolved in acetone and deposited on a thin-layer silica analytical chromatography plate (Schleicher and Schüll; F 1 500; LS 254), was eluted with cyclohexane. The separated required component was extracted from the silica with acetone to give [8-^{3}H]-4*H*-cyclopenta[*def*]phenanthrene (1.2 mg, 34%), m.p. 114.5—116 °C (lit.,[19] 114—116 °C), specific activity 2.1 mCi g^{-1}.

Preliminary kinetic studies with this compound gave non-linear first-order plots and this was assumed to be due to reaction of the methylene group with n-butyl-lithium, so that tritium became incorporated in this position. (A similar problem arose in kinetic studies with fluorene.[20]) The aliphatic tritium was therefore removed under base-catalysed hydrogen exchange conditions, as was successfully employed with fluorene.[20] The product (1 mg) was therefore heated under reflux with sodium hydroxide (0.5 g) in ethanol (2.5 ml) during 1 h and then poured into water and extracted in the usual way. The resultant product then gave excellent first-order kinetics.

Kinetic Studies.—The general method has been described previously.[21] Rate coefficients could be duplicated to better than ±1.5%, the exchange rate coefficients (10^7 k/s^{-1}) at 70° C being (positions in parentheses): 2 570 (1), 540 (2), 1 330 (3), 660 (8).

We thank the Cancer Campaign for financial assistance.

[1/409 *Received*, 12*th March*, 1981]

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