Reactions of carbonyl compounds in basic solutions. Part 26.[1] The mechanisms of the base-catalysed cyclisation of 1,2-diacetylbenzene, 1,8-diacetylnaphthalene, 4,5-diacetylphenanthrene and 2,2′-diacetylbiphenyl

Keith Bowden * and Andrew Brownhill

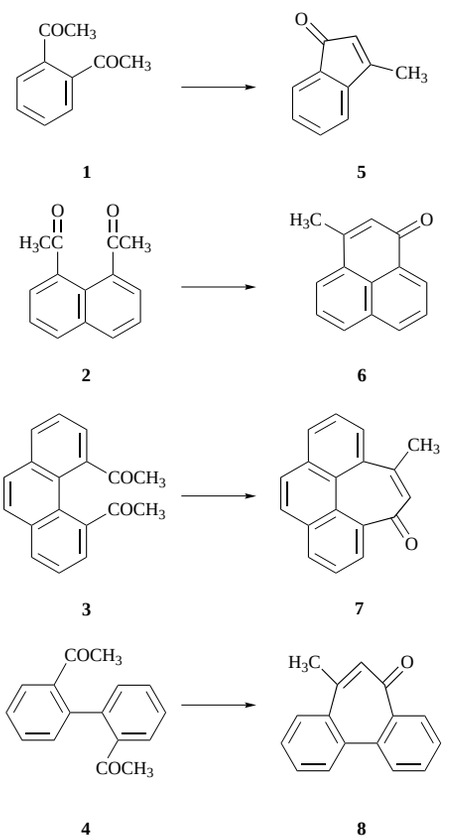
Department of Biological and Chemical Sciences, Central Campus, University of Essex, Wivenhoe Park, Colchester, Essex, UK CO4 3SQ

Rate coefficients have been measured for the base-catalysed cyclisation of 1,2-diacetylbenzene 1, 1,8-diacetylnaphthalene 2, 4,5-diacetylphenanthrene 3 and 2,2′-diacetylbiphenyl 4 in a range of aqueous dimethyl sulfoxide (DMSO) compositions at 30.0 °C, as well as at 45.0 and 60.0 °C at certain concentrations, containing tetramethylammonium hydroxide. For three of the substrates, 1, 2 and 4, the di-[$^2H_3$]acetyl compounds were also studied. Studies of the relative rates, activation parameters, kinetic isotope and solvent isotope effects and correlation of the rates with an acidity function were made to give detailed mechanistic pathways. Thus, 2, 3 and 4 react with rate-determining base-catalysed ionisation to give the enolate anion, followed by relatively rapid intramolecular nucleophilic attack and dehydration to give the corresponding cyclic enones; whereas, 1 reacts by the same pathway but with rate-determining intramolecular nucleophilic attack. An intermolecular base-catalysed aldol reaction was also detected for the product of the intramolecular reaction of 2 at high DMSO contents.

The aldol condensation and closely related reactions are extremely important in synthetic organic chemistry.[2] However, until recently, little was known about the detailed mechanisms of intramolecular aldol reactions. Nevertheless, the Claisen condensation,[3] which is also a very important synthetic process, had been mechanistically investigated previously as an intramolecular reaction. Thus, the base-catalysed cyclisation of a number of keto esters has been studied in detail and shown to proceed *via* the base-catalysed ionisation of the neighbouring carbon acid, followed by intramolecular nucleophilic attack by the enolate anion.[4,5] The rate-determining step depends on the nature of the substrate.

Very recently, a number of base-catalysed intramolecular aldol reactions of keto-aldehydes have received detailed attention.[6–8] The base-catalysed cyclisation of 2-(2-oxopropyl)benzaldehyde to 2-naphthol has been shown to proceed *via* a base-catalysed enolisation, followed by intramolecular nucleophilic attack by the enolate anion on the formyl group.[6] This is followed by a relatively rapid dehydration process to give the final product. A cyclodextrin-bis(imidazole), an enzyme mimic, has been used to catalyse the intramolecular aldol reaction of 1-(4-*tert*-butylphenyl)hexan-1,6-dione and of 2-(4-*tert*-butylphenyl)hexane-1,6-dione.[7] The reactions proceeded *via* enolisation, followed by intramolecular attack, being strongly base-catalysed and showing regioselectivity. The intramolecular aldol condensation of a substituted 1-phenylheptane-3,7-dione to give 2-benzyl-3-hydroxycyclohexanone and, subsequently, 2-benzylcyclohex-2-enone has been studied.[8] As in the previous study,[6] in dilute buffer, base-catalysed enolisation is the rate-determining step; whereas, in concentrated buffer, enolisation is relatively fast and the intramolecular cyclisation process becomes rate determining.

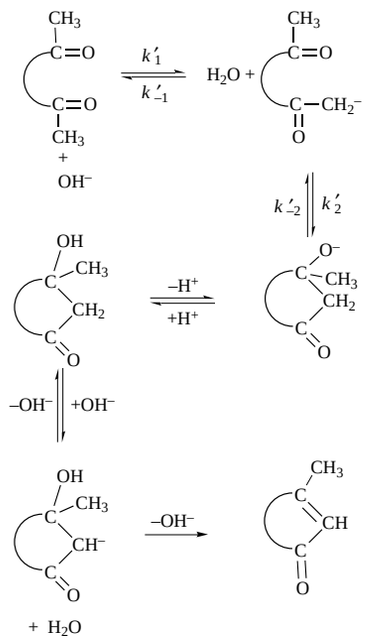
The present study presents an investigation of the intramolecular aldol reaction of a series of diacetyl compounds, set onto various aromatic templates, in aqueous dimethyl sulfoxide containing tetramethylammonium hydroxide. These are 1,2-diacetylbenzene **1**, 1,8-diacetylnaphthalene **2**, 4,5-diacetylphenanthrene **3** and 2,2′-diacetylbiphenyl **4**. The effects of structure on rates, activation parameters, kinetic isotope effects, rate-acidity function correlations and product studies have been employed to elucidate the mechanisms of the reactions.



Results and discussion

The products of the base-catalysed cyclisation reactions of the diacetyl compounds in dimethyl sulfoxide (DMSO) are the corresponding unsaturated ketones, *i.e.* **1** gives 3-methylinden-1-

one **5**, **2** gives 3-methyl-1*H*-phenalen-1-one **6**, **3** gives 11-methyl-9*H*-cyclohepta[*def*]phenanthren-9-one **7**, and **4** gives 7-methyl-5*H*-dibenzo[*a*,*c*]cyclohepten-5-one **8**. These products are given directly without the spectrophotometric observation of any intermediates, with excellent isosbestic points observed. The reactions are catalysed by hydroxide anions. At low DMSO and base concentration, the reactions have been shown to be first order in base. A reaction pathway for the base-catalysed cyclisation is shown in Scheme 1. The formation of the enolate anion



Scheme 1

is followed by intramolecular attack. The reaction is then completed by a base-catalysed dehydration to give the cyclised unsaturated ketones. It is very likely that the rate-determining steps are either the ionisation of the diacetyl compound, k'_1 in Scheme 1, or the intramolecular nucleophilic attack, k'_2 in Scheme 1. The base-catalysed dehydration in related studies appears to be relatively rapid.[6,8,9] This base-catalysed elimination would appear likely to proceed *via* an $E1_{cb}$ pathway as the β-hydroxyketone intermediate has a relatively acidic proton. Furthermore, it is driven energetically by the formation of a double-bond which is stabilised by conjugation with both the aromatic and carbonyl groups.

The rate coefficients for the base-catalysed cyclisation of the diacetyl compounds in aqueous DMSO containing tetramethylammonium hydroxide (TMAH), determined using a UV–VIS spectrophotometric method, are shown in Tables 1 and 2.

Relative rates

The order of reactivity of the diacetyl compounds in their base-catalysed cyclisation is, in general, **2** ≈ **3** > **4** ⋙ **1**. Thus, the rate coefficients of the three more reactive compounds vary, in 40 mol% aqueous DMSO, by a factor of only *ca*. 3 (by extrapolation); whereas the least reactive compound **1** is *ca*. 40 times slower than the next least reactive compound. A relative rate ratio of **2** to **1** of *ca*. 60 in 40 mol% aqueous DMSO (by extrapolation) can be compared with that for the methoxide-catalysed cyclisation of chain (normal) methyl 8-acetyl-1-naphthoate to that of chain (normal) methyl 2-acetylbenzoate which is *ca*. 220 in 36.3 mol% methanolic DMSO (by extrapolation).[5] Furthermore, the rate coefficient, k_2, of the base-catalysed cyclisation of chain (normal) methyl 8-acetyl-1-naphthoate in 70% (v/v) aqueous dioxane at 30 °C is 1.04 dm^3 mol^{-1} s^{-1},[4] whereas, the rate coefficient, k_2, for the same reaction of 1,8-diacetylnaphthalene under identical conditions can be calculated to be 1.47 dm^3 mol^{-1} s^{-1}, or 0.735 dm^3 mol^{-1} s^{-1} if

Table 1 Rate coefficients (k_1) for the base-catalysed cyclisation of the diacetyl compounds **1**–**4** in aqueous DMSO containing 0.011 mol dm^{-3} TMAH at 30.0 °C[a]

mol% DMSO	*H*	$k_1/10^{-2}$ s^{-1} **1**	**2**	**3**	**4**
1			1.93 (1.62, 2.31)[b]		0.147
3			1.90	3.04	0.172
5	12.18		1.98	3.33	0.195
10	12.94		2.79	3.61	0.265
15	13.63		3.94	3.92	0.374
20	14.28		6.47	4.58	0.565
25	14.86		10.5	5.54	0.887
30	15.40		18.6 (2.30)[c]	6.47	1.43 (0.204)[c]
35	15.92			8.50	1.96
40	16.41	0.0683 (0.0644)[c]		9.85	2.70
45	16.84	0.0916		11.2	3.45
50	17.23	0.167			4.33
55	17.60	0.218			
60	17.93	0.346			
65	18.40	0.497	[0.893		
70	18.87	0.920	1.57_5		
75	19.30	1.03_5	2.44_5		
80	19.90	1.18	4.33_5		
85	20.50	1.37	5.96_5		
90	21.30	1.68	7.09_5][d]		
95	22.50	4.90			

[a] Rate coefficients were reproducible to ±3%. [b] In 70% (v/v) dioxane–water and dioxane–deuterium oxide, respectively. [c] For the di-[$^2H_3$]acetyl compound. [d] $k_2/10^4$ dm^3 mol^{-1} s^{-1} for formation of product of intermolecular aldol reaction of **6** (see text).

Table 2 Rate coefficients (k_2) for the base-catalysed cyclisation of the diacetyl compounds **1**–**4** in aqueous DMSO[a]

System	k_2/dm^3 mol^{-1} s^{-1} at 30.0 °C	at 45.0 °C	at 60.0 °C	λ/nm[b]
1 in 40 mol% DMSO	0.0621	0.230	0.809	402
2 in 5 mol% DMSO	1.80	4.69	12.1	362 (560)[c]
3 in 5 mol% DMSO	3.03	5.96_5	11.6	382
4 in 5 mol% DMSO	0.177	0.504_5	1.21	330

[a] See Table 1. [b] Wavelength used to follow cyclisation reactions. [c] Wavelength used to follow intermolecular aldol reaction.

the statistical effect of two acetyl groups is taken into consideration. Thus, the two rates are quite similar. As both reactions apparently involve rate-determining ionisation of an 8-substituted 1-naphthyl methyl ketone, their rates would be expected to be very similar, as 8-substituents have only very small polar effects[10] and the steric 'bulk' effects of the acetyl and carbomethoxy groups should be comparable. Thus, the results above suggest that the diacetyl compounds **2**, **3** and **4**, all methyl aryl ketones, cyclise with rate-determining base-catalysed enolisation of one of the two equivalent acetyl groups; whereas **1** cyclises with rate-determining intramolecular nucleophilic attack, following a relatively rapid pre-equilibrium ionisation.

Kinetic isotope and solvent isotope effects

The rate coefficients for the base-catalysed cyclisation of three of the diacetyl compounds **1**, **2** and **4** have been measured for both the diacetyl and di-[$^2H_3$]acetyl compounds, as shown in Table 1. The values of k_1^H/k_1^D are 1.0_6, 8.0_9 and 7.0_1 for the compounds **1** (in 40 mol% aqueous DMSO), **2** and **4** (in 30 mol% aqueous DMSO), respectively. The magnitude of these kinetic isotope effects clearly indicates the nature of the rate-determining step. For compounds **2** and **4**, the ionisation process, k_1' in Scheme 1, is rate determining. Thus, a value of k^H/k^D equal to *ca*. 5–7 has been found for a number of reactions having the ionisation of methyl aryl ketones as the rate-determining step.[4,5,11] The results for the present investigation

Table 3 Activation parameters for the base-catalysed cyclisation of the diacetyl compounds **1**–**4** in aqueous DMSO at 30.0 °C[a]

System	$\Delta H^{\ddagger}$/kcal mol^{-1}[b]	$\Delta S^{\ddagger}$/cal mol^{-1} K^{-1}[b]
1 in 40 mol% DMSO	16.6	−9
2 in 5 mol% DMSO	12.1	−18
3 in 5 mol% DMSO	8.4	−29
4 in 5 mol% DMSO	12.3	−22

[a] Values of $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are considered accurate to within ±300 cal mol^{-1} and ±2 cal mol^{-1} K^{-1}, respectively. [b] 1 cal = 4.184 J.

Table 4 The slopes (l) of the rate–acidity function correlations[a]

Substrate	l	r
1	0.28 (±0.02)	0.967
2	0.30 (±0.02)	0.987
3	0.12 (±0.07)	0.979
4	0.28 (±0.01)	0.997
6	0.32 (±0.04)	0.965

[a] r is the correlation coefficient.

are slightly more complex as the 'second' acetyl group is also isotopically substituted. However, this should not affect the rate of the ionisation process to a significant degree. While the extent of carbanion formation cannot be estimated exactly, the carbanion must be highly developed in the transition state and the proton *ca.* 50% transferred.

For compound **1**, the intramolecular nucleophilic attack, k_2' in Scheme 1, is rate determining. The small value of k^{H}/k^{D} observed for this substrate arises from either a small 'inductive' effect or a change in hybridisation of the carbanion carbon from sp[3] to sp[2][12] which occurs in the cyclisation process, both of which may arise from the only partial exchange of deuterium in both acetyl groups of the substrate.

The kinetic solvent isotope effect has been measured in 70% (v/v) dioxane–water or –deuterium oxide as shown in Table 1 for **2** as substrate. The value of $k_1^{H_2O}/k_1^{D_2O}$ found in this study of 0.70 is almost identical to that found for the base-catalysed cyclisation of chain methyl 8-acetylnaphthoate (0.69) and arises from the greater basicity of the deuteroxide anion in deuterium oxide than hydroxide anion in water.[4]

Activation parameters

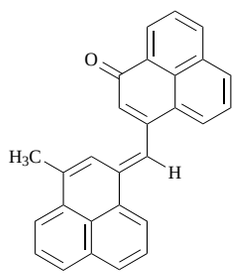
The activation parameters at 30 °C for the base-catalysed cyclisation of **2**, **3** and **4** in 5 mol% aqueous DMSO and of **1** in 40 mol% aqueous DMSO are shown in Table 3. The results of a preliminary study[13] of the base-catalysed cyclisation of **2** in aqueous ethanol is in general agreement with the present results. The activation parameters in 40 mol% DMSO for **1** are significantly different from those for **2**, **3** and **4** in 5 mol% DMSO, which may well be associated with the switch in the nature of the rate-determining step. The enthalpy of activation, $\Delta H^{\ddagger}$, for **3** is significantly less than that for **2** and **4**. This probably relates to the release of unfavourable interactions in the very 'crowded' initial state of the substrate **3** on forming the transition state. The entropy of activation, $\Delta S^{\ddagger}$, for **4** is comparable to that of **2** and **3** and indicates that the conformation of the 2,2′-disubstituted biphenyl system is already favourably situated in the initial state for reaction.

Correlation of reaction rates with the acidity function

The rates of base-catalysed cyclisation of the diacetyl compounds in aqueous DMSO containing hydroxide can be related to the acidity function, H_-, for the medium.[14] Reasonable linear relations between log k_1 and H_- are observed for all the substrates and the slopes (l) are shown in Table 4. The significance of such slopes of correlations has been considered in previous studies.[4,5] The increase in rate with decreased water and increased DMSO content arises mainly from the decreased requirement of the transition, compared to the initial, state for protic solvation, as well as the ability of DMSO to solvate charge-extended structures. However, it has been considered that the slopes of these correlations do not allow the details of the mechanisms to be reliably assigned. However, a number of correlations which involve the simple base-catalysed ionisation of methyl aryl ketones do have slopes (l) equal to *ca.* 0.4 to 0.5.[4,5,11] The significantly decreased value of l observed for **3** may well arise from severe steric compression at the carbonyl groups inhibiting solvation both in the initial and transition state.

Intermolecular reaction

Compound **2** was unique among the diacetyl compounds in that it gave a second base-catalysed reaction of high DMSO contents. The product of this reaction was shown to be the product of an intermolecular aldol reaction, *i.e.* 3-(3-methyl-1*H*-phenalen-1-ylidenemethyl)-1*H*-phenalen-1-one **9** (see

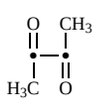


9

Experimental section). This must arise from the aldol condensation of **6** with itself. Scheme 2 shows a reaction pathway involving the enolate anion of **6**, which, unlike the enolate anions of the diacetyl compounds, is derived from a prop-2-en-1-one. The reaction was observed as a second-order process in substrate in the formation of the product (see Table 1 and Experimental section). The base-catalysed reaction rates can also be correlated with the acidity function, H_- for the medium,[14] as shown in Table 4. The rate-determining step would appear to be k_2' in Scheme 2 which is the nucleophilic attack of the carbanion on the carbonyl group of the second molecule of the ketone. This is very similar to the pathway suggested[15] for the base-catalysed intermolecular aldol reaction of methyl ketones and benzaldehyde, which is a reaction that is first order in all three species, *i.e.* base, ketone and aldehyde. The reason why the reaction is observed here for **6** and not for **5**, **7** or **8** is not obvious. Acetophenone has a pK_a of *ca.* 24.7 in DMSO[16] and the acidities of **1**–**4** would be expected to be similar. The acidities of **5**–**8** do not appear to have been measured. However, **5** is an almost angle-strain free system, unlike **6**, **7** and **8**.

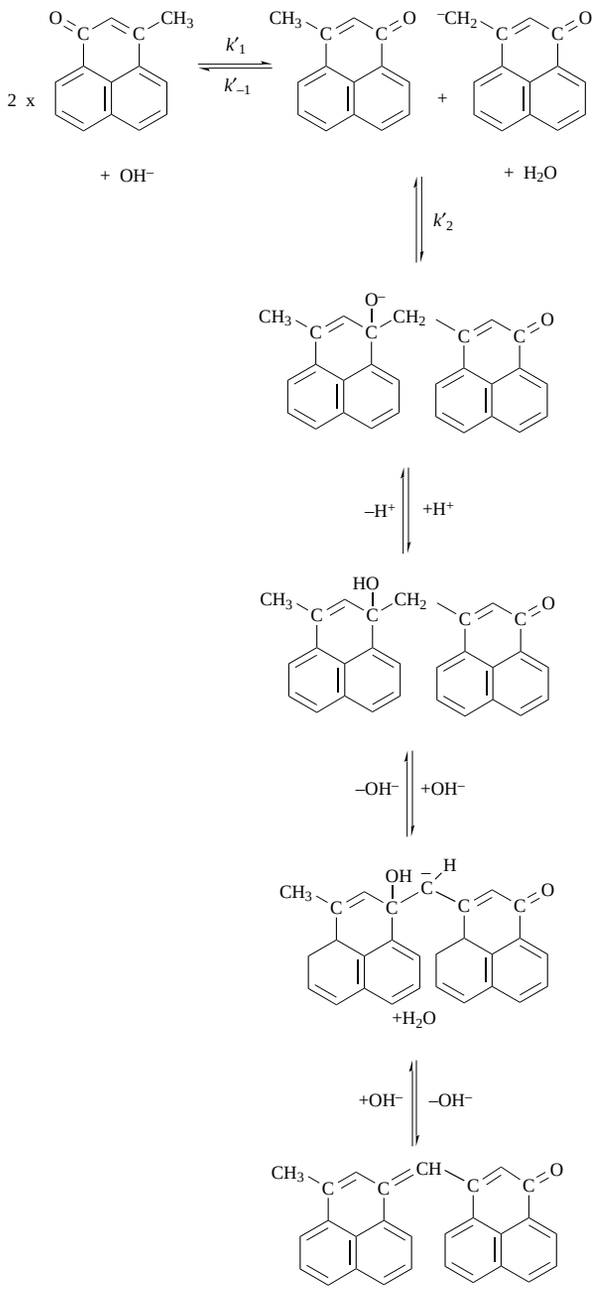
Relation between structure and detailed mechanism

Consideration of molecular models (Catalin) and molecular graphics[17] clearly indicate that both the acetyl groups in **2** and **3** are nearly completely deconjugated with the aromatic template, *i.e.* almost orthogonal; even causing some minor distortions of the aryl rings. Moreover, the acetyl groups take up the s-*trans* conformation **10** as previously discussed and detected in chain



10

(normal) methyl 8-acyl-1-naphthoates.[18] Thus, **2** has been described as having a '*transoid*' conformation.[13] This conformation minimises both unfavourable steric 'bulk' and electrostatic interactions in the 1,8-disubstituted naphthalene and 4,5-disubstituted phenanthrene systems. The generation of a car-



Scheme 2

banion on the first acetyl group in such a conformation is very favourably situated for intramolecular nucleophilic attack on the second acetyl group. The interatomic distances and plane of attack are close to that which has been considered ideal in the structural circumstances. Thus, for **2**, the first methyl carbon–second carbonyl carbon distance is *ca*. 2.04 Å and the plane of approach is orthogonal to the carbonyl groups; but the angle of approach is only 43°. The approach of a nucleophile to the carbonyl carbon–oxygen bond considered ideal is perpendicular or 109° to the plane of the carbonyl double-bond system, with the enolate double-bond being orientated antiperiplanar to the carbonyl group.[19] The conformations of 2,2′-disubstituted biphenyls are more complex. The benzene rings in **4** will be almost orthogonal due to the 'bulky' 2- and 2′-acetyl groups;[20] while each acetyl group will be almost coplanar with its own benzene ring. A conformation that minimises the unfavourable electrostatic interactions will bring a methyl group proximate to the other acetyl carbonyl group carbon. Thus, the three substrates **2**, **3** and **4**, which have a rate-determining enolisation, have very favourable stereochemical situations for the intramolecular nucleophilic attack.

Table 5 Physical constants of previously unreported products

		Found (%) (Required)	
	Mp/°C	C	H
7 ($C_{18}H_{12}O$)	112[a]	88.7 (88.5)	5.1 (4.9)
9 ($C_{28}H_{18}O$)	200[b]	91.2 (90.8)	4.7 (4.9)

[a] Colourless crystalline solid. [b] Yellow needles from cyclohexane.

On the other hand, the likely stable conformation of **1** would have an angle between the plane of the carbonyl groups and that of the benzene ring of *ca*. 45°, which will minimise unfavourable steric and electrostatic interactions and maximise the favourable resonance interactions. However, the carbonyl groups would still be s-*trans* to minimise unfavourable electrostatic interactions. Furthermore, **1** does not have either the rigid stereochemistry of **2** and **3** or the favourable bond distance–angle features. The ionisation of **1** will often be achieved without the 'in-built' stereochemistry for favourable intramolecular nucleophilic attack. Thus, **1** will have a rate-determining intramolecular nucleophilic attack, preceded by a relatively fast equilibrium ionisation.

The four templates, 1,2-benzene, 1,8-naphthalene, 4,5-phenanthrene and 2,2′-biphenyl have been employed in a number of reactions involving intramolecular catalysis and their relative ability to facilitate and control such reactions has been reviewed.[21]

Experimental

Materials

1,2-Diacetylbenzene **1**, 1,8-diacetylnaphthalene **2**, 4,5-diacetylphenanthrene **3** and 2,2′-diacetylbiphenyl **4** were prepared by the reaction of *o*-phthalaldehyde, acenaphthenequinone, 4,5-pyrenequinone and 9,10-phenanthraquinone, respectively, with the Grignard reagent, methylmagnesium iodide; followed by oxidation of resulting diols with chromium(VI) oxide, lead(IV) tetraacetate or magnesium nitrate–potassium permanganate.[22,23] The latter preparations were repeated using [$^2H_3$]methyl iodide to give the di-[$^2H_3$]acetyl compounds corresponding to **1**, **2** and **4**. Three of the products of the cyclisation reactions 3-methylinden-1-one **5**, 11-methyl-9*H*-cyclohepta[*def*]-phenanthren-9-one **7** and 7-methyl-5*H*-dibenzo[*a*,*c*]cyclohepten-5-one **8**, were synthesised by the base-catalysed cyclisation of **1**, **3** and **4**.[24,25] However, 3-methyl-1*H*-phenalen-1-one **6** was prepared by the oxidation of 1,2-dimethylacenaphthene-1,2-diol by chromic anhydride.[22,25] The product of the intermolecular aldol reaction, 3-(3-methyl-1*H*-phenalen-1-ylidenemethyl)-1*H*-phenalen-1-one **9**, was synthesised by treatment of **6** with excess aqueous sodium hydroxide (4 mol dm^{-3}) in aqueous DMSO at 30 °C. The reaction was monitored by taking aliquots and subjecting them to UV–VIS spectrophotometric analysis. The reaction was found to complete after 24 h and the product was isolated by acidification (HCl). The yield was 90% of theory. After repeated recrystallisation to constant mp from suitable solvents and drying under reduced pressure (P_2O_5), the mps of the diacetyl compounds and the reaction products were either in good agreement with literature values[22–25] or are shown in Table 5. The only exception is that **8**, reported in the literature[13] as a yellow oil, was obtained as a colourless oil, bp 220 °C at 760 mmHg. The ^{1}H and ^{13}C NMR mass and IR spectra confirmed the structures shown. The deuteriation (monitored by ^{1}H NMR spectroscopy) occurred to >98% in the di-[$^2H_3$]acetyl compounds.

The solvents for the kinetic studies were prepared as previously described.[27]

Measurements

Rate coefficients for the base-catalysed cyclisations and aldol

reactions were determined spectrophotometrically by use of a Perkin-Elmer lambda 5 or 16 UV–VIS spectrometer. The reactions were followed at the wavelengths shown in Table 2, which were normally those of the greatest differences between the substrate and product. A Haake thermostatted water circulating bath was used to control the temperature of the cell to ±0.05 °C. The procedure used was that described previously.[28] The substrate concentration was 5×10^{-5} to 1×10^{-4} mol dm^{-3}. The second-order rate coefficients for the formation of intermolecular aldol reaction were calculated as described by Espenson.[29] The products of the kinetic reactions were confirmed spectrophotometrically by comparison with the isolated products in basic solution. The values of the acidity function, H_-, were those interpolated from literature[14] values.

Acknowledgements

A. B. thanks the UK SERC for a research studentship.

References

1 Part 25. A. Al-Najjar, K. Bowden and M. V. Horri, *J. Chem. Soc., Perkin Trans. 2*, 1997, 993.
2 A. T. Neilson and W. J. Houlihan, *Org. React.*, 1968, **16**, 1.
3 C. R. Hauser, F. W. Swamer and J. T. Adams, *Org. React.*, 1954, **8**, 59.
4 K. Bowden and A. M. Last, *J. Chem. Soc., Perkin Trans. 2*, 1973, 351.
5 K. Bowden and M. Chehel-Amiran, *J. Chem. Soc., Perkin Trans. 2*, 1986, 2035.
6 R. W. Nagorski, T. Mizerski and J. P. Richard, *J. Am. Chem. Soc.*, 1995, **117**, 4718.
7 J. M. Desper and R. Breslow, *J. Am. Chem. Soc.*, 1994, **116**, 12 081; R. Breslow, J. Desper and Y. Huang, *Tetrahedron Lett.*, 1996, **37**, 2541.
8 T. Koch, J.-L. Reymond and R. A. Lerner, *J. Am. Chem. Soc.*, 1995, **117**, 9383.
9 D. S. Noyce, W. A. Pryor and A. H. Bottini, *J. Am. Chem. Soc.*, 1955, **77**, 1402.
10 K. Bowden and D. C. Parkin, *Can. J. Chem.*, 1969, **47**, 185.
11 R. P. Bell and B. G. Cox, *J. Chem. Soc.* (*B*), 1970, 194.
12 V. J. Shiner, Jr., in *Isotope Effects in Chemical Reactions*, eds. C. J. Collins and N. S. Bowman, Van Nostrand Reinhold, New York, 1970.
13 B. M. Davis, P. H. Gore, K. A. K. Lott, E. L. Short and H. G. Shinouda, *J. Chem. Soc., Perkin Trans. 2*, 1981, 58.
14 D. Dolman and R. Stewart, *Can. J. Chem.*, 1967, **45**, 911.
15 D. S. Noyce and W. L. Reed, *J. Am. Chem. Soc.*, 1959, **81**, 625.
16 F. G. Bordwell, *Acc. Chem. Res.*, 1988, **21**, 456.
17 J. Appleyard and M. J. C. Crabbe, *Desktop Molecular Modeller* (*version 2.0*), Oxford University Press, Oxford, 1991.
18 K. Bowden and A. M. Last, *J. Chem. Soc., Perkin Trans. 2*, 1973, 1144.
19 P. Deslongchamps, in *Stereoelectronic Effects in Organic Chemistry*, Pergamon Press, Oxford, 1983; H. B. Burgi, J. D. Dunitz and E. Shefter, *J. Am. Chem. Soc.*, 1973, **95**, 5065.
20 L. L. Ingraham, in *Steric Effects in Organic Chemistry*, ed. M. S. Newman, Wiley, New York, 1956, ch. 9; M. R. Abbaszadeh and K. Bowden, *J. Chem. Soc., Perkin Trans. 2*, 1990, 2081.
21 K. Bowden, in *Organic Reactivity: Physical and Biological Aspects*, eds. B. T. Golding, R. J. Griffin and H. Maskill, Royal Society of Chemistry, Cambridge, 1995, p. 123.
22 S. Goldschmidt and A. Zoebden, *Can. J. Chem.*, 1966, **44**, 1323.
23 W. Trapp and T. Zincke, *Liebigs Ann. Chem.*, 1905, **362**, 342; W. Trapp and T. Zincke, *Liebigs Ann. Chem.*, 1905, **363**, 302; S. Goldschmidt and A. Zoebden, *Chem. Ber.*, 1961, **94**, 169; R. Creigee, E. Hager, G. Huber, P. Kruck, F. Marktsheffel and H. Schevenberger, *Liebigs Ann. Chem.*, 1956, **599**, 81.
24 S. Toma, E. Solcaniova and D. G. Leppard, *Acta Fac. Rerum. Nat. Univ. Comeniannae, Chim.*, 1982, **30**, 7 (*Chem. Abstr.*, 1983, **98**, 160892u).
25 E. Laarge, F. Grimm and R. Stoermer, *Chem. Ber.*, 1917, **50**, 959.
26 R. Creigee and L. Kraft, *Annalen*, 1933, **507**, 159; D. M. Hall, J. E. Ladbury, M. S. Lesslie and E. E. Turner, *J. Chem. Soc.*, 1956, 3474; D. E. Cooke and J. Turner, *J. Chem. Soc.*, 1937, 117.
27 K. Bowden and M. J. Price, *J. Chem. Soc.* (*B*), 1971, 1748; K. Bowden and R. S. Cook, *J. Chem. Soc.* (*B*), 1971, 1765; 1771.
28 K. Bowden and A. M. Last, *J. Chem. Soc., Perkin Trans. 2*, 1973, 345.
29 J. H. Espenson, *Chemical Kinetics and Reaction Mechanisms*, McGraw-Hill, New York, 2nd edn., 1991, ch. 2.

Paper 6/06399C
Received 17*th September* 1996
Accepted 23*rd December* 1996