Some reactions of ammonia and primary amines with propanal, 2-chloroethanal, 2,2-dichloroethanal and 2,2,2-trichloroethanal in acetonitrile

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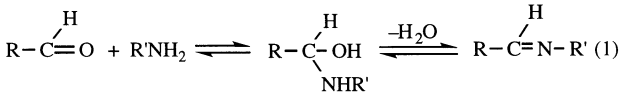
The reaction of ammonia with propanal in acetonitrile produces the hexahydrotriazine, 1, in good yield. The corresponding reaction of chloroethanal yields the cyclic trimer 16 but only in poor yield. Increasing chloro-substitution in the aldehyde stabilises the initially formed carbinolamines and disfavours trimerisation. Imines formed by reaction of primary amines with the aldehydes are relatively stable. Those formed from aliphatic amines may undergo slow dimerisation by C–C bond formation and this may be accompanied by loss of amine to yield products containing a conjugated double-bond system.

Kinetic and equilibrium data are reported for both the forward and reverse reactions involving interconversion of propanal and ammonia with 1 in acetonitrile–water mixtures. The results indicate that dehydration of the carbinolamine is rate determining.

The reactions[1–4] of aliphatic aldehydes with ammonia or primary amines may yield carbinolamines which subsequently dehydrate to give imines [reaction (1)]. It is known that imines formed from ammonia readily trimerise to yield hexahydrotriazine derivatives.[5] The imines formed from primary amines are prone to dimerisation or polymerisation, although the literature is often unclear regarding the exact nature of the products of these processes.[1–4,6–9] Previous studies have involved the reactants without solvent or in aqueous solution necessitating the removal of water from hydrated products.[10,11]



$$R{-}CH{=}O + R'NH_2 \rightleftharpoons R{-}CH(OH)(NHR') \xrightleftharpoons{-H_2O} R{-}CH{=}N{-}R' \quad (1)$$

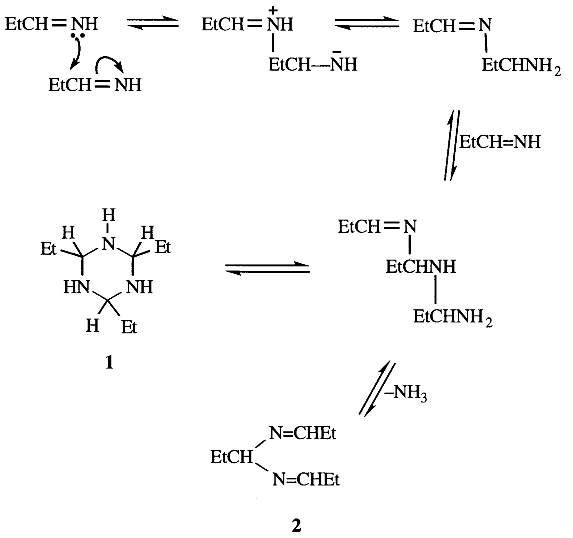
It has recently been shown that amine–carbonyl condensation reactions may be usefully carried out in acetonitrile. Thus, in this solvent the reaction of glyoxal with benzylamine derivatives yields hexabenzylhexazaisowurtzitane, an interesting cage compound.[12–15]

We report here the results of some studies of the reactions in acetonitrile of ammonia and primary amines with propanal and with 2-chloroethanal, 2,2-dichloroethanal and 2,2,2-trichloroethanal. We have routinely followed the progress of these reactions using ^1H NMR spectroscopy. However in several cases products have been isolated. We also report some kinetic and equilibrium data of the reaction of propanal with ammonia leading to the formation of the hexahydrotriazine derivative.

Results and discussion

Reaction of propanal and ammonia

The reaction of propanal (0.1 mol dm^{-3}) with an excess of ammonia (1.0 mol dm^{-3}) was followed by ^1H NMR spectroscopy in [$^2H_3$]acetonitrile (*J* values in Hz). Bands due to the aldehyde at δ 9.71 (CHO, triplet, *J* 1.3), 2.43 (CH_2, qd, *J* 7.3 and 1.3) and 1.02 (CH_3, t, *J* 7.3) gradually decreased in intensity while those of the hexahydrotriazine, **1**, increased. The ring hydrogen of **1** has δ 3.44 (t, *J* 6.1) the CH_2 group δ 1.38 (multiplet) and the CH_3 group δ 0.92 (t, *J* 7.4). After 24 h conversion of propanal was >90%. The spectra provide no evidence for the accumulation of intermediates and a limit of <5% can be set on their relative concentration. Acidification of the product resulted in the re-emergence of the bands due to propanal showing the reversibility of the reaction when the ammonia is removed by conversion to its ammonium salt. The reaction to give **1** is likely to involve N–C bond formation between imine intermediates followed by proton transfer as shown in Scheme 1. A synthetic experiment in acetonitrile as solvent gave, in good yield, a sample of **1** which was identical to a sample prepared in aqueous solution.[5] Mass spectrometric analysis of **1** indicated the formation of *N,N′*-dipropylidene-1,1-diaminopropane, **2**, formed by loss of ammonia from the molecular ion of the linear trimer of the imine. Kinetic and equilibrium results for formation of **1** are reported below.



Scheme 1

Reaction of propanal with primary amines

The reactions were followed by ^1H NMR spectroscopy in [$^2H_3$]acetonitrile using equimolar concentrations, 0.2 mol dm^{-3}, of propanal and each of the amines, *tert*-butylamine, butylamine, isopropylamine, benzylamine and aniline. Spectra were recorded immediately upon mixing and then regularly

Table 1 NMR data for **3** and **6** formed from propanal and primary amines in [$^2H_3$]acetonitrile (see Scheme 2 for lettering) (J values in Hz)

	δ									
	CH_3^a	CH_2^b	CH^c	CH^d	CH_3^e	R	J_{ab}	J_{bc}	J_{ce}	J_{be}
3a	1.01	2.17	7.63	—	—	1.11	7.5	4.6	—	—
3b	1.01	2.17	7.63	—	—	0.90, 1.30, 1.50, 3.30	7.5	4.6	—	—
3c	1.01	2.14	7.66	—	—	3.23, 1.07	7.5	4.3	—	—
3d	1.06	2.20	7.63	—	—	4.50, 7.2–7.4	7.5	4.4	—	—
3e	1.14	2.40	7.85	—	—	7.0–7.4	7.5	4.2	—	—
6a	1.02	2.25	5.89	7.84	1.76	1.16	7.5	7.4	1.4	0.8
6b	1.02	2.24	5.87	7.80	1.77	0.91, 1.30, 1.53, 3.41	7.5	7.4	1.4	0.8
6c	1.02	2.24	5.87	7.83	1.76	3.33, 1.11	7.5	7.4	1.4	0.8
6d	1.03	2.26	5.95	7.96	1.80	4.60, 7.1–7.4	7.5	7.4	1.4	0.8

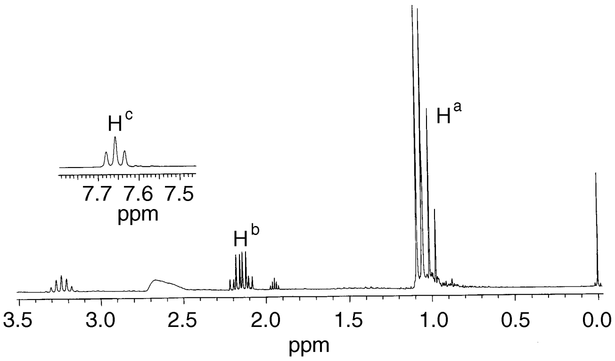


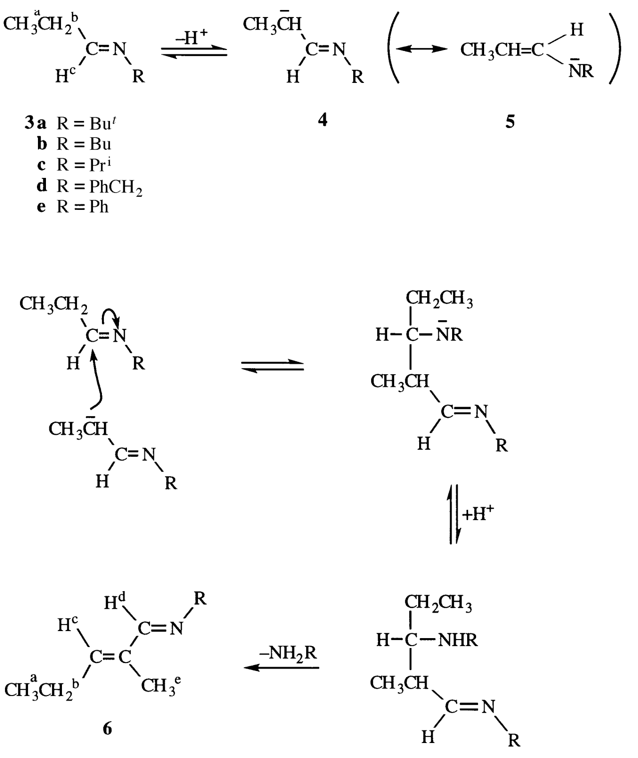
Fig. 1 ^1H NMR spectrum of the imine **3c** formed from propanal and isopropylamine in [$^2H_3$]acetonitrile. See Scheme 2 and the text for assignments.

until no change occurred. Benzylamine, isopropylamine and butylamine react rapidly and quantitatively (>95%) to give the imines **3b–d** in the favoured *syn*-conformation.[16] The spectrum of **3c** formed from isopropylamine is shown in Fig. 1. The methine hydrogen, H^c, gives a triplet, J 4.3 at δ 7.66, while the methylene group, CH_2^b, gives a quartet of doublets, J 7.5 and 4.3 at δ 2.14. The methyl group, CH_3^a, gives a triplet, J 7.5 at δ 1.01. Bands due to the isopropyl group are at δ 3.23 (septet, J 6.3) and 1.07 (d, J 6.3). The broad band at δ 2.7 is due to water formed in the dehydration of the carbinolamine intermediate, broadened presumably by exchange with the amino hydrogens of a small quantity of residual isopropylamine. The pentet at δ 1.95 is from traces of [$^2H_2$]acetonitrile in the solvent. Formation of **3a** from *tert*-butylamine occurred more slowly, possibly due to steric hindrance, but was complete after several hours. Data are given in Table 1.

Further reaction, during a period of one week, of the imines, **3a–d** resulted in the formation of *N*-substituted-2-methylpent-2-en-1-ylidenamines, **6a–d**. As shown in Scheme 2, these resulted from imine dimerisation and elimination of amine. Conversion to **6** proceeded to >90% without the accumulation of intermediates observable by ^1H NMR. The spectrum, Fig. 2, at completion of the benzylamine reaction shows bands due to **6d** at δ 7.96 (CH^d), 7.30 (Ph), 5.95 (CH^c), 4.60 (Benzyl CH_2), 2.26 (CH_2^b), 1.80 (CH_3^e), 1.03 (CH_3^a). Close examination of the spectrum indicated long range spin-coupling between CH_3^e and CH^c, J 1.4, CH_3^e and CH_2^b, J 0.8. These coupling constants are in the expected range for alkenes,[17] but do not distinguish between the two possible rotational isomers of **6**. NOE experiments indicated that the configuration about the double bonds is as shown in structure **6**.

The spectrum in Fig. 2 also shows bands due to the eliminated benzylamine at δ 7.3 (Ph), 3.75 (CH_2) and 2.41 (NH_2 together with H_2O).

NMR data for **6a–d** are in Table 1. The formation of **6a–d** from **3a–d** was also monitored by GC–mass spectrometry. In the case of the benzylamine adduct the results showed the conversion of **3d** with *m/z* 147 to **6d** with *m/z* 187. In a preparative experiment **6d** was produced in high yield.



Scheme 2

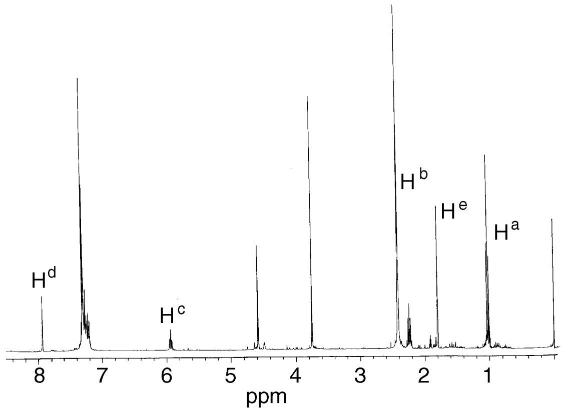


Fig. 2 ^1H NMR spectrum of **6d** formed from propanal and benzylamine in [$^2H_3$]acetonitrile. See Scheme 2 and the text for assignments.

A likely pathway for formation of **6** is shown in Scheme 2. In the presence of base a low concentration of anion **4** may be formed so that carbon–carbon bond formation results in dimerisation. Elimination of amine leads to the product in which the double bonds are conjugated. This pathway appears to be general for aliphatic amines. The failure of imines **3** to trimerise by carbon–nitrogen bond formation, as observed, Scheme 1, with the imine from ammonia may derive partially from the lack of a labile proton attached to nitrogen. Nevertheless, it is known[1–4]

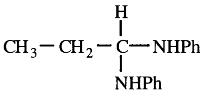
Table 2 ^{1}H NMR shifts for products of reaction of chloral with amines[b] (see Scheme 3 for lettering)

	CH^a	NH	R
8a	4.74 (d, *J* 10)	1.8 (d, *J* 10)	1.16
8c	4.65	broad	1.06, 3.14
8d	4.56 (d, *J* 9)	2.4 (broad)	4.0[c] (q, *J* 13.8) 7.2–7.5
8e	5.49 (d, *J* 9.4)	2.4 (broad)	6.7–7.3
9a	7.78	—	1.25
9c	7.89	—	1.18, 3.71
9d	8.01 (t, *J* 1.4)	—	4.81 (d, *J* 1.4) 7.2–7.5
9e	8.16	—	6.7–7.5
10a	7.91 (d, *J* 1.5)[d]	—	1.31
	8.22 (d, *J* 12.1)	—	1.28
10c	7.97		1.11, 4.00
10d	8.17		4.37, 7.2–7.5

[b] In spectra containing **10** a band due to $CHCl_3$ was observed at δ 7.60. [c] Methylene hydrogens are non-equivalent and give an AB quartet, *J* 13.8. [d] Isomeric forms observed due to restricted rotation about the C–N bond.

that imines formed from aliphatic amines and formaldehyde may form cyclic trimers. Hence steric factors may be responsible here.

In the anions **4** charge delocalisation is possible involving the form **5**. The latter distribution is likely to be favoured in the anion formed from the imine **3e** produced from propanal and aniline. It is interesting that our NMR results show that **3e** does not dimerise to give **6e** but instead, in the presence of excess aniline yields *N*,*N*′-diphenyl-1,1-diaminopropane **7**. This



$$CH_3-CH_2-\overset{\displaystyle H}{\underset{\displaystyle NHPh}{C}}-NHPh$$

7

shows bands at δ 1.0 (CH_3), 1.76 (CH_2) and 4.74 (CH) with coupling of *ca.* *J* 7 together with bands due to the phenyl hydrogens at δ 6.6–7.2. The propensity for imines formed from aniline to add a further molecule of amine has been noted previously.[18]

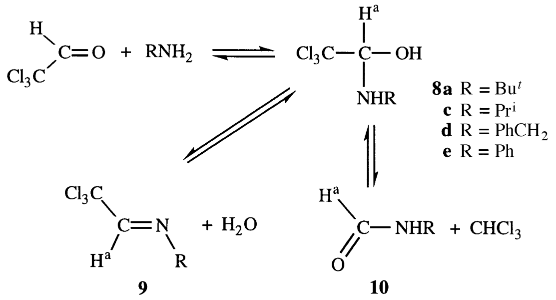
Reaction of 2,2,2-trichloroethanal (chloral) with primary amines

The ^{1}H NMR spectrum of chloral in [$^2H_3$]acetonitrile shows a singlet at δ 9.19. It is known[19] that in water chloral is strongly hydrated with an equilibrium constant of 2.8 × 10^4. The presence of 1% (v/v) of water in acetonitrile was sufficient to yield the hydrate, δ 5.14. Reaction of anhydrous chloral in acetonitrile with one equivalent of *tert*-butylamine, isopropylamine, benzylamine or aniline resulted in the rapid (<3 min) and quantitative (>90%) formation of the carbinolamines **8a–e**. The CH hydrogens absorbed at *ca.* δ 4.6 and, in the absence of rapid proton exchange, coupling *J* 10, was observed with the amino hydrogen. The presence of the electron withdrawing trichloromethyl group stabilised the carbinolamines so that further reaction took several hours. Those formed from aliphatic amines reacted by loss of water to yield imines **9a,c,d** and competitively by elimination of chloroform to yield *N*-alkylformamides **10a,c,d**. In anhydrous solvent the imines were favoured over the formamides in a ratio of *ca.* 3:1. However, use of solvent which had been exposed to air, allowing the absorption of water, favoured formation of the formamides, **10**. In solvent containing 1% (v/v) added water, reaction occurred quantitatively (>95%) to yield the formamides. However in the presence of a two-fold excess of chloral, which will act as an efficient dehydrating agent, the imines **9** were produced quantitatively, >95%. Spectroscopic data are in Table 2. There was no evidence for dimerisation or polymerisation of the imines **9**.

Table 3 ^{1}H NMR data for products of reaction of 2,2-dichloroethanal with amines (see Scheme 4 for lettering)

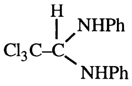
	δ				
	H^a	H^b	H^c	R	J_{ab}/Hz
12c	5.81	4.55	—	1.06, 3.10	2.5
12f	5.84	4.63	—	—	2.6
13a	6.21	7.61	—	1.13	6.3
13c	6.23	7.70[d]	—	1.13, 3.50	6.3
13d	6.30	7.82	—	4.66, 7.1–7.5	6.3
14a	6.47	4.71	7.75	1.19, 1.21	1.8
14c	6.48	4.68	7.84[d]	1.13, 1.15, 3.54, 3.57	1.8
14d	6.47	4.69	7.95[e]	4.66, 4.70, 7.1–7.5	1.8

[d] Long range coupling, *J* 0.7, is observed between H^b and the isopropyl CH. [e] Long range coupling, *J* 1.4, is observed between H^c and the benzyl CH_2 group.



Scheme 3

The carbinolamine **8e** from reaction with aniline underwent slow dehydration to yield **9e**, but loss of chloroform to give **10**, was not observed. At equilibrium the hydrate **8e** was favoured relative to the imine **9e**. Dehydration could be effected by the use of excess ethanal. In the presence of excess aniline there was evidence for formation of **11** (δ 5.67, t, *J* 8) by addition to the imine.



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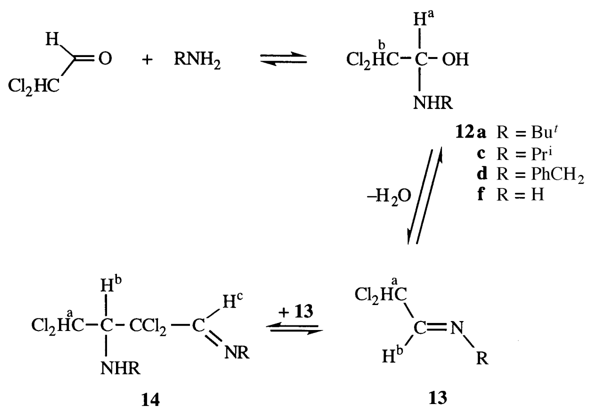
The reactions of 2,2-dichloroethanal with ammonia and primary amines

The aldehyde shows bands at δ 6.24 and 9.32 (*J* 1.7). In the presence of added water, the hydrate absorbs at δ 5.04 and 5.70 (*J* 3.1). Reaction of the aldehyde with ammonia in [$^2H_3$]acetonitrile resulted in the rapid and quantitative (>90%) formation of the carbinolamine **12f**, which was stable for several hours. However, there was no evidence of dehydration to yield the corresponding imine and over several days decomposition occurred to give unidentified products. The ^{1}H NMR spectrum at completion showed a large number of small peaks.

Reaction of 2,2-dichloroethanal with aliphatic amines in anhydrous acetonitrile yielded the imines **13a,c,d** quantitatively (>90%). However, reaction with isopropylamine in solvent containing water allowed the detection of the carbinolamine **12c** which slowly yielded the corresponding imine **13c**. Spectroscopic data are in Table 3.

The ^{1}H NMR spectra provide evidence for the dimerisation of the imines **13** over a period of several days to yield **14**. An interesting feature is the low value of the coupling constant observed between H^a and H^b. This is likely to reflect steric crowding which prevents free rotation about the C–C bond. It is known[17] that vicinal coupling constants vary with dihedral angle. A value of *J* 1.8 observed in **14** corresponds to a dihedral angle of 90 ± 30°.

The reactions observed are outlined in Scheme 4. The mechanism of dimerisation is likely to be analogous to that shown in Scheme 2 for the dimerisation of the propanal imines. Carban-



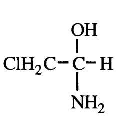
Scheme 4

ion formation at the dichloromethyl group may lead to C–C bond formation. However, unlike the propanal case, elimination of amine from the dimers, **14**, is not observed. Formation of a conjugated double bond system is not possible here since the relevant carbon atom adjacent to that carrying the amino group does not carry a hydrogen atom.

The reaction of 2-chloroethanal with ammonia and primary amines

The anhydrous aldehyde in [$^2H_3$]acetonitrile shows bands at δ 9.54 and 4.25, J 1.0. In the presence of water, bands were observed due to the hydrate at δ 5.00 and 3.45, J 4.7.

Reaction in acetonitrile with ammonia yielded the carbinolamine **15** with bands at δ 3.56 and 4.70, J 4.4, attributed to the CH_2Cl and CH hydrogens respectively. No bands due to the imine, 2-chloroethylideneamine, were observed. However over a period of hours there was evidence for the formation of the hexahydrotriazine, **16**, in low yield (<10%). Bands were observed at δ 3.66 (d, J 4.0) due to CH_2Cl, 4.03 (t, J 4.0) due to CH and 2.13 due to amine hydrogens. These bands corresponded precisely to those from a sample of **16** isolated from reaction in aqueous solution. The low yield of **16** may be due to competitive self-polymerisation of the parent aldehyde.[20]



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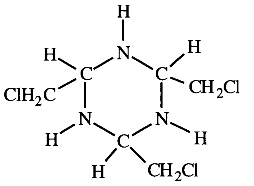


16

Reaction of 2-chloroethanal with aliphatic amines in [$^2H_3$]-acetonitrile yielded the imines **17** with >90% conversion. Data are in Table 4. There was evidence for dimerisation with the elimination of amine, as shown in Scheme 5, in an analogous fashion to that observed with the imine from propanal. However, this reaction only proceeded to completion with the imine from isopropylamine. Further reaction of **17a** and **17d** yielded unidentified decomposition products.

Conclusions

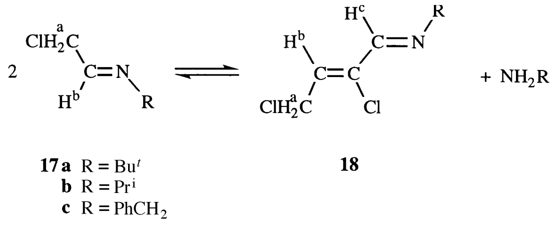
The main conclusions of the NMR study in acetonitrile are that the reaction of ammonia with propanal produces the hexahydrotriazine **1** in good yield, but **16** is formed from chloroethanal only in poor yield. Increasing chloro-substitution in the aldehyde stabilises the carbinolamines and disfavours trimerisation possibly by reducing the nucleophilicity of the nitrogen atoms of the incipient imines.

Imines formed from reaction of primary amines with the aldehydes are relatively stable. Our results provide definite evidence for the nature of the further reactions of imines where the literature is uncertain. They show that those formed from aliphatic amines may undergo slow dimerisation by C–C bond formation and this may be accompanied by loss of amine to yield products containing a conjugated double-bond system.

Table 4 NMR data for products of reaction of chloroethanal with amines (see Scheme 5 for lettering)

	δ				
	H^a	H^b	H^c	R	J_{ab}
17a	4.08	7.61	—	1.16	4.8
17c	4.07	7.66^d	—	1.11, 3.41	4.9
17d	4.15	7.80^e	—	4.60, 7.2–7.5	4.7
18a	4.44^f	6.55^f	7.94	1.21	
18c	4.43	6.52	7.98	1.31, 3.44	7.6

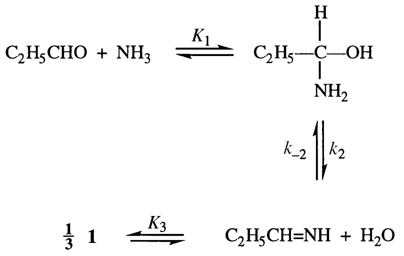
^{d} Long-range coupling, J 0.6, observed with isopropyl CH. ^{e} Long-range coupling, J 1.3, observed with benzyl CH_2. ^{f} Relatively broad bands, coupling constants not measured.



Scheme 5

Kinetic and equilibrium studies

Measurements have been made of the reaction of propanal with ammonia to give the hexahydrotriazine **1** in acetonitrile–water mixtures. The hydration constant of propanal in water is known[19] to have the value 0.71. Hence in media rich in acetonitrile the aldehyde will be almost completely in the unhydrated form. The progress of reactions was followed using the UV absorbance of propanal at 286 nm (ε, 17.5 dm^3 mol^{-1} cm^{-1}). The results are interpreted in terms of Scheme 6. In agreement with NMR results there was no evidence for the build up in concentration of carbinolamine or imine intermediates in the interconversion with **1**. There is excellent evidence in related systems[21] that dehydration becomes rate limiting in alkaline media. Our data, collected in Table 5, indicate that the reaction is acid catalysed suggesting that here also the dehydration–hydration step is rate-determining. On that basis we define forward and reverse rate coefficients by eqns. (2) and (3). The overall equilibrium constant is defined in eqn. (4).



Scheme 6

$$k_f = k_2K_1 \tag{2}$$

$$k_r = k_{-2}/K_3 \tag{3}$$

$$K = K_1K_2K_3 = k_f/k_r = \frac{[\mathbf{1}]^{\frac{1}{3}}}{[\text{Propanal}][\text{NH}_3]} \tag{4}$$

The measurement of the concentrations of propanal at equilibrium, using absorbance data, allowed the calculation of the

Table 5 Kinetic and equilibrium data for equilibration of propanal and ammonia with **1** in acetonitrile–water mixtures at 25 °C

Item	[Propanal]$_o$/ mol dm^{-3}	[NH$_3$]$_o$/ mol dm^{-3}	Water (%) (v/v)	Conditions	k_{obs}/ 10^{-3} s^{-1}	k_f/ 10^{-3} dm^3 mol^{-1} s^{-1}	k_r/ 10^{-3} mol$^{2/3}$ dm^{-2} s^{-1}	Abs (286 nm)	K/dm^5 mol$^{-5/3}$
1	0.038	0.91	3.4	—	1.21	1.33	—	0.093	50
2	0.073	0.87	3.4	—	1.21	1.4	—	0.108	60
3	0.038	0.69	3.3	—	1.04	1.5	—	0.127	48
4	0.038	0.46	3.1	—	0.95	2.1	—	0.188	48
5	0.040	1.2	20	—	0.75	0.62	—	0.110	32
6	0.040	0.96	20	—	0.68	0.71	—	0.159	27
7	0.040	0.72	20	—	0.54	0.75	—	0.198	29
8	0.040	1.71	20	*a*	10.7	6.3	—	0.091	26
9	0.040	1.35	20	*a*	8.0	5.9	—	0.095	32
10	0.040	0.90	20	*a*	4.7	5.2	—	0.144	31
11	0.049	0.96	20	*b*	11.6	12	—	0.156	27
12	0.049	0.72	20	*b*	7.6	10.5	—	0.197	28
13	0.049	0.48	20	*b*	4.3	9	—	0.280	29
14	0.000[e]	0.048	20	*b*	—	—	—	1.36	30
15	0.000[e]	0.095	20	*b*	—	—	—	1.24	26
16	0.000[e]	0.143	20	*b*	—	—	—	0.97	31
17	0.040	1.71	50	*b*	9.8	5.7	—	0.126	16
18	0.040	1.35	50	*b*	7.7	5.7	—	0.160	15
19	0.040	0.90	50	*b*	5.0	5.6	—	0.194	18
20	0.049	1.0	20	*c*	46	46	—	—	—
21	0.049	0.80	20	*c*	35	44	—	—	—
22	0.049	0.60	20	*c*	34	56	—	—	—
23	0.049	0.40	20	*c*	18	45	—	—	—
24	0.049	0.80	20	*d*	48	60	—	—	—
25	0.049	0.60	20	*d*	31	52	—	—	—
26	0.049	0.40	20	*d*	25	63	—	—	—
27	0.000[f]	0.00	20	*c*	—	—	1.5	—	—
28	0.000[g]	0.00	20	*c*	—	—	1.5	—	—
29	0.000[f]	0.00	20	*d*	—	—	1.8	—	—
30	0.000[g]	0.00	20	*d*	—	—	1.7	—	—

[a] Buffered with [NH$_4$ClO$_4$] = 0.01 [NH$_3$]. [b] Buffered with [NH$_4$ClO$_4$] = 0.02 [NH$_3$]. [c] Buffered with [NEt$_3$] = [NHEt$_3{}^+$ClO$_4{}^-$] = 0.5 mol dm^{-3}, pH = 10.7 ± 0.1. [d] Buffered with [NEt$_3$] = 0.5 [NHEt$_3{}^+$ClO$_4{}^-$] = 0.25 mol dm^{-3}, pH = 10.4 ± 0.1. [e] Reverse reaction measured, no initial propanal. [**1**]$_o$ = 0.046 mol dm^{-3}. [f] Reverse reaction measured. No initial propanal or ammonia. [**1**]$_o$ = 0.0213 mol dm^{-3}. [g] Reverse reaction measured. No initial propanal or ammonia. [**1**]$_o$ = 0.0107 mol dm^{-3}.

equilibrium concentrations of **1** and hence values of K. The data in Table 5 show that values decrease with increasing water content in the solvent; 50 dm^5 mol$^{-\frac{5}{3}}$ at 3% water, 30 at 20% water and 16 at 50% water. These decreases may be attributed to stabilisation of the ammonia by added water. As expected the values of K are independent of the initial concentrations of the reagents and on the acidity of the medium. Identical values are obtained when the equilibrium is measured in the forward direction, items 11–13 and in the reverse direction, items 14–16.

In the general case the reactions in Scheme 6 will lead to quite complex dependences of concentration of reagents with time. To simplify the kinetics we attempted to isolate the forward and reverse reactions by working under conditions when the equilibrium will be very largely in favour of products and reactants, respectively. The former condition was achieved using ammonia in large excess of propanal. Here first-order kinetics were observed and values of k_f could be calculated from values of k_{obs} using eqn. (5).

$$k_{obs} = k_f[\mathrm{NH_3}] \tag{5}$$

The reverse reaction was studied starting from the hexahydrotriazine, **1**. When this reaction is dominant eqn. (6) may be derived as shown.

$$\frac{-\mathrm{d}[\mathbf{1}]}{\mathrm{d}t} = \frac{1}{3}\frac{\mathrm{d}[\text{propanal}]}{\mathrm{d}t}$$

$$= \frac{1}{3}\frac{k_{-2}}{K_3}[\mathbf{1}]^{\frac{1}{3}}$$

After integration

$$[\mathbf{1}]^{\frac{2}{3}} = [\mathbf{1}]_o^{\frac{2}{3}} - \frac{2}{9}\frac{k_{-2}}{K_3}t \tag{6}$$

where [**1**]$_o$ is the initial concentration of hexahydrotriazine. Plots of [**1**]$^{\frac{2}{3}}$ *versus* time allowed the calculation of values of k_{-2}/K_3. A plot corresponding to item 30 of Table 5 is shown in Fig. 3.

The data in Table 5 show that values of k_f are independent of the initial concentration of propanal, items 1 and 2, or ammonia, items 1, 3 and 4 or 5–7. They decrease with increasing water content in the solvent accounting for the corresponding decreases in value of K. Values of k_f are increased by the presence of ammonium perchlorate, items 8–10 and 11–13, consistent with acid catalysis. Problems associated with using ammonia–ammonium perchlorate buffers were the relative insolubility of the salt in acetonitrile and the difficulty in isolating the reverse reaction, due to the initial presence of one of the reactants. Values of k_f and k_r in the same medium were obtained using triethylamine–triethylammonium perchlorate buffers, items 20–30. It is known[22] that in acetonitrile the pK_a values of triethylamine (18.46) and ammonia (16.46) are well separated. This difference is likely to be maintained in acetonitrile–water mixtures, so that the ammonia concentration will not be essentially depleted by protonation by the buffer. The data in Table 5 show that in buffer c, pH 10.7, values of k_f and k_r are 0.045 dm^3 mol^{-1} s^{-1} and 0.0015 mol$^{\frac{2}{3}}$ dm^{-2} s^{-1}, respectively. Combination of these values leads to a value for K of 30 dm mol$^{-\frac{5}{3}}$ in good agreement with that obtained from equilibrium absorbance data in the same medium. In the buffer d, pH 10.4, values are 0.060 dm^3 mol^{-1} s^{-1} and 0.0018 mol$^{\frac{2}{3}}$ dm^{-2} s^{-1} yielding a similar value, 33 dm^5 mol$^{-\frac{5}{3}}$, for K.

The kinetic results are consistent with the proposed scheme, indicating that dehydration of the carbinolamine is rate determining in the formation of hexahydrotriazine. The results suggest that the rate of reactions may be increased by acid catalysis and that yields will be improved in acetonitrile compared to water as solvent.

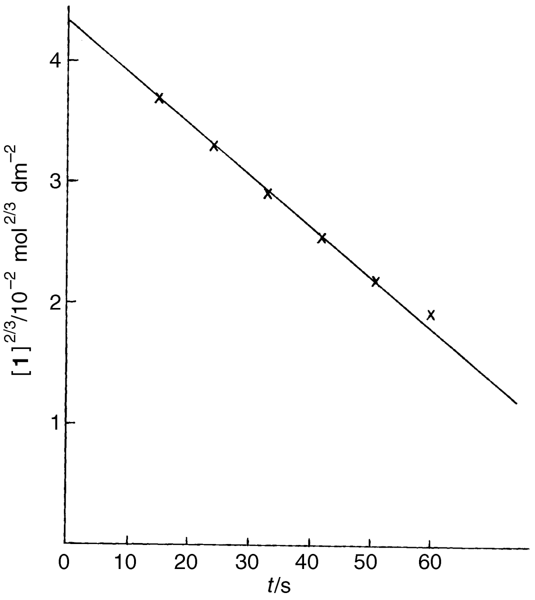


Fig. 3 A plot according to eqn. (6) under the conditions of item 30 in Table 5.

Experimental

Propanal, 2-chloroethanal and 2,2,2-trichloroethanal were the purest available commercial specimens. 2,2-Dichloroethanal was prepared from its diethyl acetal;[23] to 1,1-dichloro-2,2-diethoxyethane (50 g) was added benzoic anhydride (65 g) and conc. sulfuric acid (5 cm^3) and the mixture was heated on an oil bath fitted with a vigreux column to 210 °C. The product (19.9 g, 62%) distilled at 86 °C. Amines, acetonitrile and [$^2H_3$]-acetonitrile were the purest available commercial specimens. Distilled water was boiled to expel carbon dioxide and was then protected from the atmosphere.

NMR spectra were recorded using Varian-200 XL or VXR-400 spectrometers. UV spectra and kinetic measurements were made with a Beckman Lambda 2 spectrophotometer thermostatted at 25 °C. First-order rate constants were determined by following changes in absorbance at 286 nm and analysing the data using standard methods. Values are precise to ±10%. Values of the reverse rate coefficient were determined using eqn. (6); absorbance values, corresponding to the ethanal produced, were used to calculate the residual concentrations of **1**.

Preparation of 2,4,6-triethyl-1,3,5-hexahydrotriazine, 1

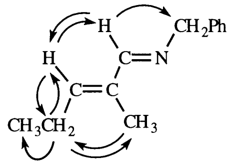
The compound was synthesised from propanal and ammonia in water using the method described by Nielsen *et al.*[5] It was found that the synthesis could be conveniently carried out in acetonitrile. Dry ammonia gas (8.5 g, 0.5 mol) was dissolved in acetonitrile and propanal (6.0 g, 0.1 mol) was added to the solution. The mixture was left for 15 h, dried with magnesium sulfate and filtered. Evaporation of the solvent using a rotary evaporator gave (3.1 g, 55%) of **1**. ^{1}H NMR spectra of the samples prepared by the two methods were identical and showed no detectable impurities (<5%). Mass spectrometric analysis showed a major fragment *m/z* 154 attributed to the product **2** formed by loss of ammonia from **1**.

2,4,6-Tri(chloromethyl)-1,3,5-hexahydrotriazine, 16

2-Chloroethanal (32 g, 0.4 mol) was slowly added to concentrated aqueous ammonia (120 cm^3, 2 mol) at 5 °C. The mixture was stored at 0 °C for 5 d followed by the addition of sodium chloride. The solution was stirred at 25 °C for 1 h and was then extracted with diethyl ether (4 × 100 cm^3). The ether extract was dried with magnesium sulfate, filtered and the solvent was removed on a rotary evaporator. Further pumping at 0.1 mbar yielded **16** (1.0 g, 3%).

N-Benzyl-2-methylpent-2-ene-1-imine, 6d

To propanal (0.5 mol) in acetonitrile (400 cm^3) was added benzylamine (0.5 mol) and the solution was stirred at 25 °C for 5 d. The acetonitrile was then removed using a rotary evaporator and the resulting mixture was distilled under reduced pressure (10 mmHg) using a vigreux column. Benzylamine distilled at 65 °C and **6d** (0.2 mol, 80%) at 129 °C. ^{1}H NMR data are in Table 1. NOE irradiations were carried out at δ 1.8, 2.3, 5.93 and 7.94 and indicated the strong interactions shown below. The ^{13}C spectrum showed bands at 11.4 (CH$_3$), 13.4 (CH$_3$), 21.7 (CH$_2$), 64.5 (NCH$_2$), 126.6, 127.6, 128.1, 135.3 (Ph), 139.7 and 143.9 (C=C) and 166.7 (C=N). The mass spectrum, VG7070E, showed a molecular ion at *m/z* 187. The UV spectrum gave λ_{max} 230 nm (ε 2.24 × 10^4 dm^3 mol^{-1} cm^{-1}).



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