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NMR Study of the Monomer–Dimer Equilibria of Dimethylnitrosobenzenes in Solution. Identification of Mixed Azodioxy Dimeric Species

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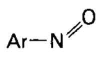
The monomer–dimer equilibria of 2,6- and 3,5-dimethylnitrosobenzenes in $CDCl_3$ solution were investigated by ^1H and/or ^{13}C NMR spectroscopy. The mixed systems nitrosobenzene + 2,6-dimethylnitrosobenzene and 2,6-dimethylnitrosobenzene + 3,5-dimethylnitrosobenzene were also studied, and mixed azodioxy dimers were identified. In all systems exchange occurs exclusively between dimer and monomer species, rates and activation energies being calculated from time-dependent ^1H 1D spectra and/or ^1H 2D-EXSY spectra measured at different temperatures.

KEY WORDS ^1H NMR ^{13}C NMR 2,6-Dimethylnitrosobenzene 3,5-Dimethylnitrosobenzene Monomer–dimer equilibria Mixed azodioxy dimers

INTRODUCTION

Aromatic *C*-nitroso compounds have been known for many years to exist as blue or green monomers (**A**) or colourless azodioxy dimers.[1–5] *Cis–trans* distinction occurs between the dimeric structures (**B**, **C**):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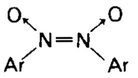
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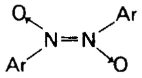
C

and indeed both crystalline forms have been isolated in the case of *o*-nitrosotoluene.[6] In organic solvents monomer–dimer equilibria are established with both *cis* and *trans* dimers usually co-existing.[7] In a recent NMR study[8] of nitrosobenzene (NB) in $CDCl_3$, we have shown that both dimeric species are formed at low temperatures but the population of the *trans* dimer is low ($\leqslant 6\%$). It was also shown by 2D-EXSY experiments that exchange occurs between the monomer and dimer species and there is no direct *cis* dimer–*trans* dimer exchange. We have now applied similar NMR techniques to 2,6-dimethylnitrosobenzene (2,6-DMNB) and 3,5-dimethylnitrosobenzene (3,5-DMNB) in $CDCl_3$ solution. Previous studies of 2,6-DMNB[7,9] had identified the *trans*-azodioxy dimer as the most stable structure. In the solid state it is usually the exclusive structure, whereas in solution it is known to exist in equilibrium with the monomer. The *cis*-azodioxy dimer has never, to our knowledge, been identified in solution and this was one of the reasons that prompted us to reinvestigate this system with modern NMR techniques. No previous studies appear to have been made on the monomer–dimer equilibrium of 3,5-DMNB.

In addition to studying the solution properties of these *sym*-dimethyl aromatic nitroso compounds themselves, a further major aim was to use their methyl NMR signals to investigate whether mixed (i.e. unsymmetrical) dimers were formed in systems containing two different nitroso monomers. Such species have been predicted[10] but, except in one instance,[11] have not been isolated owing to rapid equilibration,[12] *viz.*

$$(ArNO)_2 + (Ar'NO)_2 \rightleftharpoons 2ArNO + 2Ar'NO \rightleftharpoons 2ArN(O)N(O)Ar'$$

We have examined the mixed systems NB + 2,6-DMNB and 2,6-DMNB + 3,5-DMNB with a view to identifying all the monomeric and dimeric (*cis–trans* mixed and unmixed) species and measuring their exchange properties by ^1H 2D-EXSY experiments.

EXPERIMENTAL

Compounds

Nitrosobenzene was purchased from Aldrich. 2,6-Dimethylnitrosobenzene was prepared from its nitro derivative following the procedure used for the preparation of nitrosobenzene.[13] This involves the reduction of the nitro compound to its hydroxylamine derivative using zinc–ammonium chloride in aqueous solution, followed by oxidation using acidified potassium dichromate. The crude product was purified by recrystallization from ethanol. For the preparation of 3,5-

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dimethylnitrosobenzene it was necessary to modify the procedure as follows. The reaction was carried out in water–acetone (10:1), with the oxidative step effected by using iron (III) chloride. The final product was extracted into dichloromethane and purified by chromatography on an alumina column cooled to −20 °C.

NMR studies

^{1}H and ^{13}C NMR spectra were obtained at frequencies of 250.1 and 62.9 MHz, respectively, on a Bruker AM250 spectrometer with an Aspect 3000 computer. A standard B-VT100 variable-temperature unit was used to control the probe temperature, the calibration of this unit being checked periodically against a Comark digital thermometer. The quoted spectral temperatures are estimated to be accurate to ±1 °C. Two-dimensional phase-sensitive ^{1}H EXSY spectra were obtained using the Bruker automation program NOESYPH, which uses the pulse sequence D_1–90°–D_0–90°–D_9–90°–FID. In all cases a spectral width of 150 Hz, an F_2 dimension of 512 words and an F_1 dimension of 128 words, zero filled to 512 words, were used. The 2D spectra were processed using a Gaussian window function of 0.2 Hz and left unsymmetrized. Symmetrization was not performed as it can lead to artifacts in phase-sensitive 2D spectra dominated by strong signals with axial ridges (see later). In any case, the intensities of cross-peak pairs were adjusted to the same value when preparing the intensity data for computation to rate data,[8] thus making any symmetrization procedure unnecessary. The mixing times D_9 ($=\tau_m$) used in the NOESYPH sequence are given with the rate data in Tables 1, 5 and 7. The initial relaxation delays (D_1) were usually twice the mixing times and always ⩾2 s. However, the derived rate data were insensitive to the choice of D_1. In one series of experiments, values of D_1 in the range 2–6 s gave rate constants which agreed well within their experimental uncertainties.

RESULTS AND DISCUSSION

2,6-Dimethylnitrosobenzene

Proton NMR spectra of a moderately concentrated solution (*ca.* 0.5 M) of 2,6-DMNB in CDCl$_3$ were obtained in the range 30–60 °C. At 30 °C, a strong methyl signal attributed to the *trans* dimer was detected together with a weak signal to higher frequency due to monomeric 2,6-DMNB. On raising the temperature the relative intensities of these two signals became closer as the abundance of the monomeric species increased, until by 60 °C the monomer was the more abundant species. The chemical shifts (Table 1) were similar to those reported earlier for a CD$_3$CN solution.[7] Dilution of the CDCl$_3$ solution altered the monomer/dimer population ratio. On cooling this diluted solution to −40 °C, a third methyl signal appeared to low frequency of the other two. This was clearly due to the *cis*-azodioxy dimer of 2,6-DMNB, which has not been previously detected in solution, although its presence in the solid state has been shown by IR spectroscopy.[9]

Dimer–monomer exchange rates were measured from ^{1}H 2D-EXSY experiments on a 0.5 M solution of 2,6-DMNB in the range 30–60 °C. The rate constants for *trans* dimer → monomer conversion are given in Table 1. From these data a value of 118 ± 1 kJ mol^{-1} was obtained for $\Delta H^\ddagger$ for the dissociation process, which compares with a value of 85 kJ mol^{-1} obtained by UV spectrophotometry.[9]

Using a less concentrated CDCl$_3$ solution (*ca.* 0.1 M) and heating to *ca.* 60 °C, it was possible to obtain a solution containing *ca.* 80% monomer. Rapid cooling of this solution by inserting it into a precooled NMR probe effectively freezes the monomer–*trans* dimer equilibrium at its high-temperature concentration ratio (N.B. at 0 °C a solution of this concentration at equilibrium would consist almost completely of the *trans* dimer form). The monomer, however, quickly equilibrates with the *cis* dimer over the period of a ^{1}H 2D-EXSY experiment, and rates of exchange between *cis* dimer and monomer were sufficiently fast to allow their determination using the 2D-EXSY technique at −10, −20 and −30 °C. The rate constants for *cis* dimer → monomer conversions were 0.13 s^{-1} (263 K), 0.020 s^{-1} (253 K) and 0.0031 (243 K), from which Eyring activation parameters were calculated (Table 3). The relatively low value of $\Delta G^\ddagger$ (298 K) is probably indicative of the large steric interactions between the methyl groups on the adjoining rings in the *cis* dimer, which destabilize its ground state relative to its dissociation transition state.

3,5-Dimethylnitrosobenzene

The ambient temperature (30 °C) ^{1}H spectrum of 3,5-DMNB in CDCl$_3$ showed only monomer to be present.

Table 1. Proton chemical shifts[a] and relative populations of solution species of 2,6-DMNB in CDCl$_3$

θ (°C)	2,6-DMNB	%	*trans*-(2,6-DMNB)$_2$	%	*cis*-(2,6-DMNB)$_2$	%	k(*trans*-D → M)[d]	τ_m (s)
60[b]	2.62	51.4	2.45	48.6	—	—	0.40	1.0
50[b]	2.63	34.0	2.46	66.0	—	—	0.10	1.0
40[b]	2.63	12.8	2.46	87.2	—	—	0.025	2.0
30[b]	2.64	8.4	2.46	91.6	—	—	0.0053	4.0
−40[c]	2.67	12.3	2.48	53.2	2.18	34.5	—	—

[a] Relative to Me$_4$Si.

[b] 0.5 M solution.

[c] Dilute solution. Populations do not relate to the 0.5 M solution.

[d] Uncertainties ±10%.

Table 2. Proton chemical shifts[a] and relative populations of solution species of 3,5-DMNB in $CDCl_3$

θ (°C)	3,5-DMNB	%	$(3,5\text{-DMNB})_2$	%	k (D → M) (s^{-1})	Method
30	2.45	100	—			
10	2.45	95.6	2.24	4.4	0.59	2D-EXSY[b]
0	2.45	85.7	2.23	14.3	0.29	2D-EXSY[b]
−20	2.46	69.5	2.22	30.5	6.0×10^{-3}	TD-NMR[c]
−30	2.47	50.3	2.22	49.7	3.8×10^{-4}	TD-NMR[c]
−40	2.47	41.3	2.20	58.7	1.6×10^{-4}	TD-NMR[c]

[a] Relative to Me_4Si.
[b] Using a mixing time of 3 s.
[c] Time-dependent NMR based on 3,5-methyl signals.

However, on cooling, a second methyl signal appeared (see Table 2), indicating the presence of a dimeric form, but the isomeric identification of this species is difficult. The dimeric species in the crystalline state is usually the dominant dimer species in solution,[8,14] but unfortunately no x-ray crystal structure of 3,5-DMNB has been reported. Whereas steric interactions in 2,6-DMNB dictate that the *trans* dimer be the favoured structure, no appreciable steric effects are present in 3,5-DMNB. It is partly for this reason that nitrosobenzene (NB) and 3-methylnitrosobenzene (3-MNB) exist exclusively as *cis* dimers in the solid state. However, 4-methylnitrosobenzene crystallizes as the *trans*-azodioxy dimer, so clearly crystal packing factors are also important.

Methyl proton chemical shifts [Table 1 and Ref. 7 (Table 3)] show low-frequency displacements on going from monomers to dimers, with the magnitudes of these changes decreasing as the methyl groups are positioned further from the nitroso substituent, and with *cis* dimer shifts being greater than *trans* dimer shifts. With 3-MNB the shift changes are −0.18 (monomer → *cis* dimer) and −0.08 (monomer → *trans* dimer).[7] Comparison of these values with the value of −0.27 (−40 °C) for 3,5-DMNB (Table 2) strongly implies that 3,5-DMNB is present as the *cis*-azodioxy dimer in $CDCl_3$ solution.

A study of the dynamic nature of the monomer–dimer equilibrium of 3,5-DMNB posed certain problems. At above-ambient temperatures, where the exchange rates would have been well suited for 2D-EXSY experiments, the dimer population was too low for accurate studies, whereas at low temperatures the equilibrium state was very slowly established. In order to measure exchange rates over as wide a temperature range as possible, 2D-EXSY experiments were therefore performed at 10 and 0 °C and time-dependent spectra recorded at −20, −30 and −40 °C. The 2D-EXSY experiments were carried out on the methyl signals in the usual way,[15] using a mixing time of 3 s, and the derived rate constants are given in Table 2.

The time-dependent studies involved dissolving a known amount of 3,5-DMNB in $CDCl_3$, warming to *ca.* 60 °C to produce an exclusively monomeric sample and then placing the sample in the NMR probe at the chosen temperature. When thermal equilibrium was established the relative intensities of the monomer and dimer methyl signals were measured as a function of time, for periods varying between 1 and 20 min. Assuming that the signal intensities are directly related to the relative concentrations of monomer and dimer, rate constants for the dimer → monomer exchange were calculated by the appropriate graphical treatment (see below).

Kinetics of reversible dimer (D)–monomer (M) exchange

The system is described by

$$\mathrm{D} \underset{k_{-1}}{\overset{k}{\rightleftharpoons}} 2\mathrm{M}$$

This is not a trivial kinetic problem as it involves both first- and second-order kinetics and, in the present context, no assumption can be made regarding the negligible concentration of either species at any time. Firstly, we write

$$\frac{\mathrm{d}[\mathrm{D}]}{\mathrm{d}t} = k_{-1}[\mathrm{M}]^2 - k[\mathrm{D}] \qquad (1)$$

At equilibrium $\mathrm{d}[\mathrm{D}]/\mathrm{d}t = 0$, hence $k_{-1} = k[\mathrm{D}]_e/[\mathrm{M}]_e^2$, where the subscripts e refer to equilibrium concentrations. If the total solution concentration (based on monomer moieties), $[\mathrm{M}] + 2[\mathrm{D}]$, is denoted by c and $[\mathrm{D}]_e/[\mathrm{M}]_e^2 = p$, then

$$\frac{\mathrm{d}[\mathrm{D}]}{\mathrm{d}t} = kp(c - 2[\mathrm{D}])^2 - k[\mathrm{D}] \qquad (2)$$

$$= k(pc^2 - 4[\mathrm{D}]pc + 4p[\mathrm{D}]^2 - [\mathrm{D}]) \qquad (3)$$

Therefore,

$$\frac{\mathrm{d}[\mathrm{D}]}{pc^2 - 4[\mathrm{D}]pc + 4p[\mathrm{D}]^2 - [\mathrm{D}]} = k\,\mathrm{d}t \qquad (4)$$

and

$$\int_{[\mathrm{D}]_0}^{[\mathrm{D}]_t} \frac{\mathrm{d}[\mathrm{D}]}{4p[\mathrm{D}]^2 - (4pc + 1)[\mathrm{D}] + pc^2} = \int_0^t k\,\mathrm{d}t \qquad (5)$$

Integration of Eqn (5) (see Appendix) yields the rate law

$$\ln\left(\frac{x[\mathrm{D}]_t + a}{y[\mathrm{D}]t + b}\right) = -q_{\mathrm{D}}kt \qquad (6)$$

where the parameters a, b, x, y and q_{D} are functions of the concentrations c, $[\mathrm{D}]_0$ and $[\mathrm{D}]_e$ (see Appendix). The dimer → monomer rate constant, k, can therefore be deduced from the slope of the graph of the logarithmic function in Eqn (6) versus time. The values calculated for the temperatures −20, −30 and −40 °C are given in Table 2. These values were then combined with

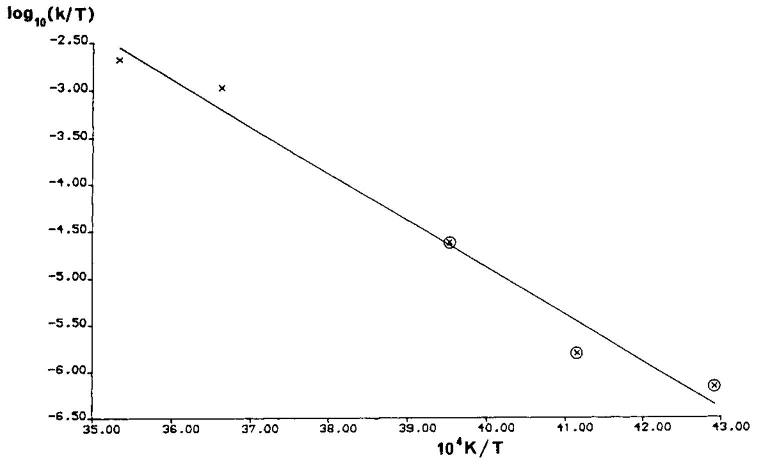

Figure 1. Eyring plot of rate data for the dissociation of *cis*(?)-$(3,5\text{-DMNB})_2$. ⊗, Time-dependent NMR derived rate constants; ×, 2D-EXSY derived values.

the 2D-EXSY values and plotted according to the Eyring rate theory (Fig. 1) to yield activation energy data (Table 3.) The rate constants derived by these two methods appear to be consistent and vindicate this combination of 1D and 2D NMR methods for measuring very slow chemical exchange rates.

2,6-Dimethylnitrosobenzene + nitrosobenzene

Having gained knowledge of the solution equilibria of 2,6-DMNB and NB separately, their two-component mixture in $CDCl_3$ was investigated with the particular objective of identifying any mixed 2,6-DMNB–NB dimers which might be formed and measuring their exchange properties with their respective monomers.

Both ^1H and ^{13}C spectra of an equimolar mixture of 2,6-DMNB + NB were recorded in the range 60 to −50 °C.

^1H NMR studies

At 60 °C only two methyl signals were observed due to 2,6-DMNB monomer and *trans*-$(2,6\text{-DMNB})_2$ dimer. On cooling to 40 °C, two additional signals appeared to lower frequencies at δ 2.37 and 2.29. These were clearly due to the mixed dimers, and comparison of chemical shifts (Table 1) led to the higher frequency signal being attributed to *trans*-(2,6-DMNB–NB) and the other signal to *cis*-(2,6-DMNB–NB). On gradual cooling to −50 °C all signal intensities changed such that the 2,6-DMNB monomer population fell sharply, the *trans*-$(2,6\text{-DMNB})_2$ concentration decreased slightly (but was always dominant) and the two mixed dimers increased in population, particularly the *cis*-(2,6-DMNB–NB) which became the second most abundant solution species at the lowest temperatures (Table 4). It should be clearly recognized that these relative populations are based on methyl signal strengths and therefore cannot allow for the presence of NB monomer at ambient temperatures and NB monomer and *cis*-$(NB)_2$ dimer at low temperatures.[8] The population changes in the mixed system are reflected in the spectra recorded at 30 and −50 °C shown in Fig. 2. Figure 2 also depicts the changes in the aromatic signals. These were not fully assigned, but the signals in the range δ 7.4–7.0 are attributed to the 2,6-DMNB (monomer + dimer) protons and the higher frequency signals (δ 8.1–7.5) to the monomer and dimer NB protons. More specifically, the weak doublet at $\delta = 7.0$ is attributed to the 4-position proton of the DMNB ring of *cis*-(2,6-DMNB–NB) and the weak multiplet at δ 8.05 is probably due to the 2,6-protons of the NB ring of one of the dimeric species.

Table 3. Activation parameters for the dissociation of aromatic nitroso compounds in $CDCl_3$ solution

Compound	Process	ΔG^*(298 K) (kJ mol^{-1})	ΔH^* (kJ mol^{-1})	ΔS^* (J K^{-1} mol^{-1})	Ref.
2,6-DMNB	*trans*-D → M	87.9 ± 0.1	118 ± 1	100 ± 3	This work
	trans-D → M	78.7[a]	85	21	9
	cis-D → M	64.9 ± 0.4	97 ± 2	108 ± 10	This work
3,5-DMNB	*cis*(?)-D → M	68.3 ± 1.4	96 ± 8	93 ± 32	This work
2,6-DMNB + NB	*trans*-D[b] → M	79.44 ± 0.01	112 ± 6	110 ± 19	This work
	cis-D[b] → M	71.96 ± 0.03	97 ± 10	85 ± 32	This work
2,6-DMNB + 3,5-DMNB	*trans*-D[b] → M	79.15 ± 0.01	83 ± 3	14 ± 19	This work
	cis-D[b] → M	72.6 ± 0.1	98 ± 5	85 ± 18	This work
NB	*trans*-D → M	70.0 ± 0.3	94 ± 4	82 ± 16	8
	cis-D → M	65.8 ± 0.1	89 ± 1	76 ± 3	8

[a] Calculated from Ref. 9.
[b] Mixed, unsymmetrical dimer.

Table 4. Relative populations and chemical shifts of solution species arising from 2,6-DMNB + NB in $CDCl_3$

θ (°C)	2,6-DMNB	*trans*-(2,6-DMNB)$_2$	*trans*-(2,6-DMNB–NB)	*cis*-(2,6-DMNB–NB)
	Relative populations[a] (%)			
40	24.6	51.8	13.1	10.6
30	13.8	51.3	17.0	17.9
20	10.7	50.1	17.5	21.7
10	5.0	46.3	19.0	29.8
0	2.4	47.7	17.1	32.8
−10	0.6	48.2	16.8	34.5
−50	—	48.1	18.4	33.6
	Chemical shifts, δ (rel. to Me_4Si)			
30[b]	2.64	2.47	2.36	2.28
−30[c]	—	19.1[d]	17.3[d]	17.8[d]
		129.4[e]	123.8[f]	123.3[f,g]

[a] Error limits ±2%.
[b] ^1H shifts.
[c] ^{13}C shifts.
[d] Methyl signals.
[e] 3,5-Carbons.
[f] 2,6-Carbons (NB ring).
[g] Also signals at 124.6, 143.1 due to *cis*-(NB)$_2$.

^{13}C NMR studies

Proton decoupled ^{13}C spectra of the mixture were recorded at 30 and −30 °C. At the higher temperature signals due to *trans*-(2,6-DMNB)$_2$ and monomeric NB were observed and assignments were possible in most cases. In addition, weak signals due to traces of 2,6-DMNB monomer were also detected. On cooling to −30 °C the spectrum became predictably more complex and 31 signals were detected, four of these being very weak and attributed to traces of the monomers of 2,6-DMNB and NB. The remaining 27 signals represent the full complement expected for the species *trans*-(2,6-DMNB)$_2$, *cis*-(NB)$_2$, *cis*-(DMNB–NB) and *trans*-(DMNB–NB). The signals were grouped into four main spectral regions, namely δ 17–20 (methyl carbons), δ 121–125 (2,6-carbons, NB rings), δ 129–137 (3,5- and 4-carbons), and δ 141–144 (1-carbons). The four main solution species at −30 °C are characterized by their methyl and/or 2,6- and 3,5-carbon signals (Table 4).

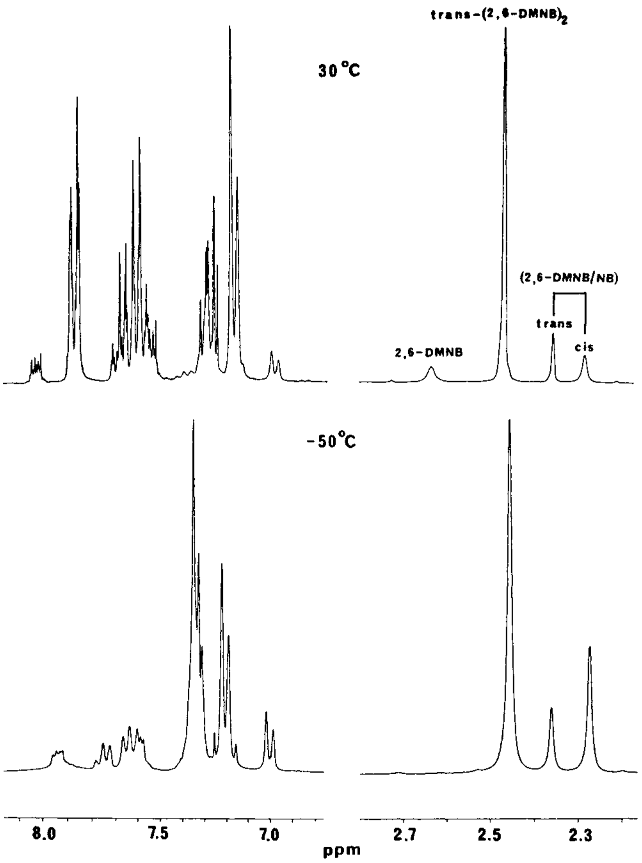

Figure 2. 250 MHz ^1H NMR spectra (aromatic + methyl regions) at 30 °C and −50 °C of 2,6-DMNB + NB in $CDCl_3$ showing the mixed dimer species (δ 2.28, 2.36). Full chemical shift and population details are given in Table 4.

Monomer–dimer exchange

Proton 2D-EXSY spectra of the methyl signals associated with this 2,6-DMNB + NB mixture were recorded in the range 10–40 °C, using mixing times ranging from 1.5 to 0.2 s. The spectrum at 40 °C is shown in Fig. 3. It is dominated by the intense signal due to *trans*-(2,6-DMNB)$_2$. This signal, however, is not involved in any exchange and its axial ridge[16] does not detract from the accuracy of the experiment. Exchange cross-peaks are clearly observed between the two mixed dimers and between the dimers and the 2,6-DMNB monomer. Volume integrals of these diagonal and cross-peak signals were measured and the D2DNMR program[15] used to evaluate the three rate constants involved from the 3 × 3 kinetic matrix.[15] The values are given in Table 5. It will be noted that the direct *cis–trans* mixed dimer exchange is negligible, implying that the detected cross-peaks for this process were second-order artifacts arising from slightly long mixing times.[15–17] This result is not surprising as it implies a negligibly slow rate of rotation about the N=N bond in the mixed 2,6-DMNB–NB dimers. Exchange therefore takes place exclusively between the mixed dimers and their parent

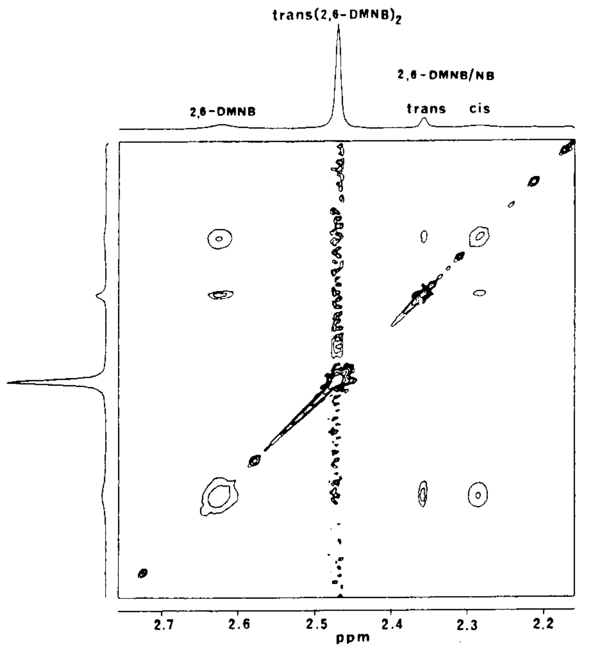

Figure 3. Methyl region 250 MHz proton 2D-EXSY spectrum of 2,6-DMNB + NB in $CDCl_3$ at 40 °C. Mixing time, 0.2 s; initial relaxation delay, 2 s.

monomers, an analogous result to that found for the NB system.[8]

The temperature dependence of the rate constants (Table 5) provided an evaluation of the activation parameters for the two processes using the standard Eyring treatment (Fig. 4). The results are given in Table 3. Since only the methyl signals were used for monitoring the exchange, no information was obtained regarding dissociation of the mixed dimers to the NB monomer. However, this dissociation should be energetically identical with that involving 2,6-DMNB monomer, since both processes involve the same transition-state intermediate.

2,6-Dimethylnitrosobenzene + 3,5-dimethylnitrosobenzene

2,6-DMNB has been shown to dimerize preferentially into the *trans* form, whereas 3,5-DMNB appears to adopt the *cis* dimer form. A mixture of these two nitroso compounds might therefore be expected to display the results of competitive formation of both *cis* and *trans* mixed dimers. A further point of interest is the steric interactions of the methyl substituents in any mixed dimer species formed.

Table 5. Rate data for dimer dissociation in the system 2,6-DMNB + NB in $CDCl_3$

		Rate constants, k (s^{-1})		
θ (°C)	τ_m (s)	*cis*-D → M[a]	*trans*-D → M[b]	*cis*-D → *trans*-D[c]
40	0.2	9.0	0.77	0.029
30	0.3	4.0	0.14	−0.041
20	1.5	0.61	0.031	0.023
10	1.5	0.19	0.007	0.003

[a] *cis*-(2,6-DMNB–NB) → 2,6-DMNB. Values accurate to ±10%.
[b] *trans*-(2,6-DMNB–NB) → 2,6-DMNB. Values accurate to ±50%.
[c] *cis*-(2,6-DMNB–NB) → *trans*-(2,6-DMNB–NB). Values are zero within experimental accuracy.

Methyl region ^1H 1D spectra of an equimolar mixture of 2,6-DMNB + 3,5-DMNB were recorded in the range 40 to −20 °C. Eight signals (plus one impurity signal) were identified at most temperatures, as depicted in the spectrum at 10 °C (Fig. 5). Comparison of methyl chemical shifts with those of the 2,6- and 3,5-DMNB components showed that the signals were probably due to the 2,6-DMNB and 3,5-DMNB monomers, the dimers *trans*-(2,6-DMNB)$_2$ and *cis*(?)-(3,5-DMNB)$_2$, and the mixed dimers *cis*- and *trans*-(2,6-DMNB–3,5-DMNB). The signals for the monomer and symmetrical dimer species were assigned without difficulty (Table 6), but the assignments of the mixed dimer signals were in doubt at this stage. In order to clarify these assignments, and at the same time to measure the dimer → monomer dissociation kinetics of this system, a series of 2D-EXSY spectra was recorded in the temperature range 0–40 °C. The spectrum at 30 °C is shown in Fig. 6. The four signals due to the mixed dimers are in two groups and, by analogy with the 2,6-DMNB + NB system, the higher frequency pair (signals 4,5) is attributed to *trans*-(2,6-DMNB–3,5-DMNB) and the other pair (signals 1,3) to *cis*-(2,6-DMNB–3,5-DMNB). Assignments within these two pairs were clearly ascer-

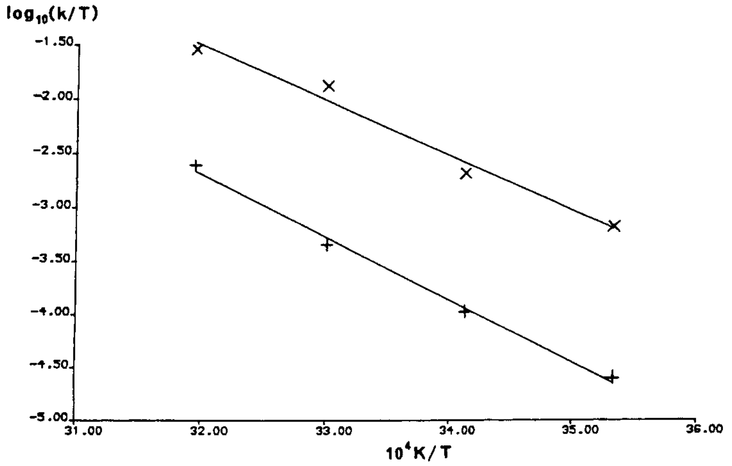

Figure 4. Eyring plot of rate data for the dissociation of (×) *cis*-(2,6-DMNB–NB) to 2,6-DMNB and (+) *trans*-(2,6-DMNB–NB) to 2,6-DMNB.

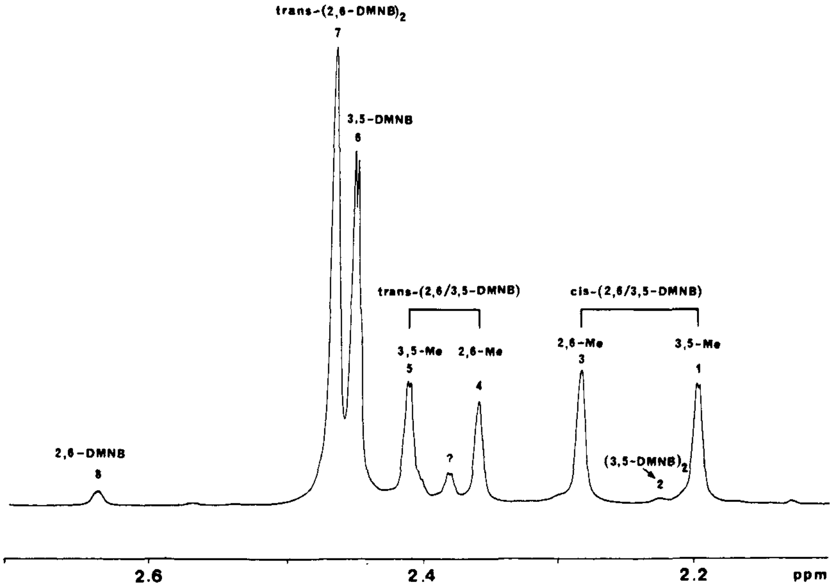

Figure 5. Methyl region 250 MHz proton spectrum of 2,6-DMNB + 3,5-DMNB in $CDCl_3$ at 10 °C showing the assignments of the solution species (signals 1–8). Note the small $^4J(H,H)$ splitting of 3,5-methyls to H-4.

tained from the 2D-EXSY spectra since the cross peaks identify the type of methyl groups (2,6- or 3,5-) common to both monomer and mixed dimer species. Exchange rate constants for this mixed system were measured employing the 3,5-methyl signals since these had a more favourable intensity distribution than the 2,6-methyl signals. Evaluated rate constants are listed in Table 7. Again, direct *cis–trans* mixed isomer exchange is negligibly slow. Eyring plots based on these data were produced and activation parameters calculated. These are given in Table 3 for comparison with the data pertaining to the other nitroso compounds.

Ground-state and dissociation transition-state energy data

The temperature dependences of the populations of the solution species enable ground-state energy data for the different equilibria to be evaluated in terms of the standard thermodynamic functions $\Delta H^{\ominus}$, $\Delta S^{\ominus}$ and $\Delta G^{\ominus}$. The magnitudes of these parameters for the pure 2,6-DMNB and 3,5-DMNB systems have been compared with those measured earlier[8] for NB (Table 8). The positive $\Delta H^{\ominus}$ values indicate that the dimeric forms of these nitroso compounds are thermodynamically preferred, which explains the solid-state dimeric structures of NB and 2,6-DMNB. The exceptionally large value for the 2,6-DMNB system reflects the particularly low ground-state energy of *trans*-(2,6-DMNB)$_2$, and the positive $\Delta G^{\ominus}$ value for its dimer ⇌ monomer equilibrium indicates that dissolution of this compound at room temperature leads to little dissociation of this dimer. The large positive $\Delta S^{\ominus}$ values for all the systems are typical of dimer–monomer dissociation equilibria. These large entropy terms cause the Gibbs function

Table 6. Methyl proton chemical shifts[a] and relative populations[b] of species for 2,6-DMNB + 3,5-DMNB in $CDCl_3$

Compound	2,6-Methyls	3,5-Methyls	Population (%)
2,6-DMNB	2.64	—	2.3
3,5-DMNB	—	2.46[c]	42.0
trans-(2,6-DMNB)$_2$	2.47	—	26.5
cis(?)-(3,5-DMNB)$_2$	—	2.23[d]	0.6
trans-(2,6-DMNB–3,5-DMNB)	2.36	2.42[c]	12.3
cis-(2,6-DMNB–3,5-DMNB)	2.28	2.20[c]	16.4

[a] At 30 °C.
[b] At 10 °C.
[c] At lower temperatures weak doublet splitting ($^4J \approx 0.5$ Hz) due to coupling to H-4 is observed.
[d] Value at 10 °C. Dimer not detectable at 30 °C.

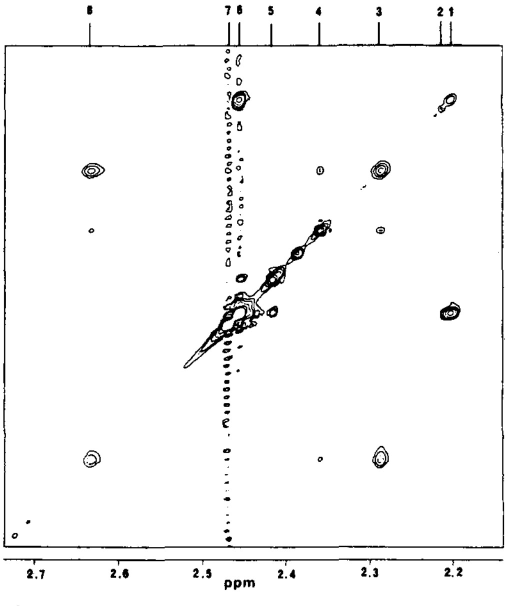

Figure 6. Proton 2D-EXSY spectrum of methyl signals in 2,6-DMNB + 3,5-DMNB in $CDCl_3$ at 30 °C. Diagonal signals are numbered according to Fig. 5. The exchanges observed are 1 ⇌ 6, 3 ⇌ 4 (second order), 3 ⇌ 8, 4 ⇌ 8 and 5 ⇌ 6.

Table 7. Rate data for dissociation of mixed dimers in 2,6-DMNB + 3,5-DMNB in $CDCl_3$

θ (°C)	τ_m[a] (s)	k(cis-D → M)[b] (s^{-1})	k(trans-D → M)[c] (s^{-1})	k(*cis*-D → *trans*-D)[d] (s^{-1})
40	0.3	6.1	0.45	[e]
30	1.0	1.9	0.15	0.011
30	0.2	2.8	[f]	[f]
20	1.0	0.73	0.042	0.002
20	0.2	0.62	[f]	[f]
10	4.0	0.15	0.014	0.001
0	4.0	0.021	[f]	[f]

[a] Mixing time in EXSY pulse sequence.
[b] *cis*-(2,6/3,5-DMNB) → 3,5-DMNB. Values accurate to ±10%.
[c] *trans*-(2,6/3,5-DMNB) → 3,5-DMNB. Values accurate to ±50%.
[d] *cis*-(2,6/3,5-DMNB) → *trans*-(2,6/3,5-DMNB). Values are zero within experimental error.
[e] No *cis* → *trans* cross-peaks were detected owing to overlap of exchange broadened signals. The calculation was adjusted to give k(*cis*-D → *trans*-D) = 0.
[f] Mixing time insufficiently long to determine these values.

changes, $\Delta G^\ominus$, to increase appreciably with decreasing temperature.

The activation parameters for the dimer-monomer dissociation pathways are given in Table 3. As usual, the $\Delta G^{\ddagger}$ values have narrower error limits. As a result of the positive entropy terms typical of dissociation equilibria, the $\Delta G^{\ddagger}$ values decrease with increasing temperature. At 298 K, values range from 88 kJ mol^{-1} for *trans*-$(2,6\text{-DMNB})_2$ to 65 kJ mol^{-1} for *cis*-$(2,6\text{-DMNB})_2$. The high value for *trans*-$(2,6\text{-DMNB})_2$, which differs significantly from that calculated from UV–visible spectrophotometry,[9] reflects the high stability of the *trans*-azodioxy form due to the electronic influence of the *ortho* methyl groups on the N=N bond. In general, the *trans* dimers of all the compounds studied dissociate more slowly than their *cis* counterparts, the difference in $\Delta G^{\ddagger}$ values varying between 4 and 7 kJ mol^{-1} in most cases. For 2,6-DMNB, however, this difference is 23 kJ mol^{-1} and arises primarily from the large difference in ground-state energies of *cis*-$(2,6\text{-DMNB})_2$ and *trans*- $(2,6\text{-DMNB})_2$. Dissociation energies of the mixed dimers appear to be very close to the average values for the unmixed dimers. For example, the $\Delta G^{\ddagger}$ value for dissociation of *trans*-(2,6-DMNB–NB) is 79.44 kJ mol^{-1}, which compares very closely with 79.0 kJ mol^{-1}, the mean of the *trans*-$(2,6\text{-DMNB})_2$ value (87.9 kJ mol^{-1}) and the *trans*-$(NB)_2$ value (70.0 kJ mol^{-1}).

CONCLUSION

The main findings of this work can be summarized as follows.

Proton NMR measurements have shown that the energy associated with dissociation of *trans*-$(2,6\text{-DMNB})_2$ in $CDCl_3$ is appreciably higher than that calculated from UV–visible spectrophotometry on a CH_2Cl_2 solution. The *cis*-azodioxy dimer, *cis*-$(2,6\text{-DMNB})_2$, has been identified for the first time in solution.

The power of combining time-dependent NMR with 2D-EXSY NMR for measuring very slow rates of exchange has been demonstrated for 3,5-DMNB in $CDCl_3$. Only one dimer of 3,5-DMNB (probably the *cis* form) was detected and its dissociation tendency in $CDCl_3$ was similar to that of NB.

The mixtures 2,6-DMNB + NB and 2,6-DMNB + 3,5-DMNB in $CDCl_3$ have been studied by 1D and 2D NMR methods and both *cis* and *trans* mixed dimers identified for the first time. Their rates of dissociation to their parent monomers have been accurately monitored by proton 2D-EXSY studies.

APPENDIX

It was shown in the main text that for a reversible first-order/second-order kinetic system

$$\mathrm{D} \underset{k_{-1}}{\overset{k}{\rightleftharpoons}} 2\mathrm{M}$$

approaching equilibrium, an integrated rate law may be obtained from

$$\int_{[\mathrm{D}]_0}^{[\mathrm{D}]_t} \frac{\mathrm{d}[\mathrm{D}]}{4p[\mathrm{D}]^2 - (4pc + 1)[\mathrm{D}] + pc^2} = \int_0^t k\,\mathrm{d}t \qquad (5)$$

Tables of standard integrals[18] give

$$\int \frac{\mathrm{d}x}{a + bx + cx^2} = \frac{1}{\sqrt{-q}} \ln\left(\frac{-2cx - b + \sqrt{-q}}{2cx + b + \sqrt{-q}}\right)(q < 0)$$

where $q = 4ac - b^2$. In Eqn (5) $a = pc^2$, $b = -4pc - 1$ and $c = 4p$. Therefore, integration of Eqn (5) gives

$$\left[\frac{1}{\sqrt{-q}} \ln\left\{\frac{-8p[\mathrm{D}] + 4pc + 1 + \sqrt{-q}}{8p[\mathrm{D}] - 4pc - 1 + \sqrt{-q}}\right\}\right]_{[\mathrm{D}]_0}^{[\mathrm{D}]_t} = [kt]_0^t$$

Now, $q = -8pc - 1$. Substitution for p and c (see main text) and rearrangement gives

$$q = -[(c + 2[\mathrm{D}]_e)/(c - 2[\mathrm{D}]_e)]^2$$

Let

$$q_\mathrm{D} = +\sqrt{-q} = (c + 2[\mathrm{D}]_e)/(c - 2[\mathrm{D}]_e)$$

Table 8. Ground-state thermodynamic data for the monomer–dimer equilibria of aromatic nitroso compounds

Equilibrium	$\Delta H^\ominus$ (kJ mol^{-1})	$\Delta S^\ominus$ (J K^{-1} mol^{-1})	$\Delta G^\ominus$ (298 K) (kJ mol^{-1})
cis-$(NB)_2 \rightleftharpoons 2$ NB	55.4 ± 1.7	213 ± 7	−8.1 ± 0.3
trans-$(NB)_2 \rightleftharpoons 2$ NB	42.5 ± 1.2	179 ± 5	−10.9 ± 0.3
trans-$(2,6\text{-DMNB})_2 \rightleftharpoons 2$ 2,6-DMNB	94.2	278	11.4
cis(?)-$(3,5\text{-DMNB})_2 \rightleftharpoons 2$ 3,5-DMNB	45.6	184	−9.3

Therefore,

$$\left[\frac{1}{q_D}\ln\left\{\frac{-8p[D]+4pc+1+q_D}{8p[D]-4pc-1+q_D}\right\}\right]_{[D]_0}^{[D]_t} = [kt]_0^t$$

This may be expressed solely in terms of dimer concentrations [D] and $[D]_e$ and total solute concentration c. Evaluation between the limits leads, after rearrangement, to

$$\ln\left\{\frac{(c^2-4[D]_e[D]_0)\,([D]_t-[D]_e)}{(c^2-4[D]_e[D]_t)\,([D]_0-[D]_e)}\right\} = -\left(\frac{c+2[D]_e}{c-2[D]_e}\right)kt$$

which can be written as

$$\ln\left(\frac{x[D]_t+a}{y[D]_t+b}\right) = -q_D kt \qquad (7)$$

where

$$a = [D]_e(-c^2+4[D]_0[D]_e) = -[D]_e x$$
$$b = c^2([D]_0-[D]_e)$$
$$x = c^2-4[D]_0[D]_e$$
$$y = 4([D]_e^2-[D]_0[D]_e) = -4[D]_e b/c^2$$

First-order dimer → monomer dissociation rate constants can therefore be evaluated from the slope of the graph of the logarithmic function [Eqn (7)] versus time.

REFERENCES

1. B. G. Gowenlock and W. Lüttke, *Q. Rev. Chem. Soc.* **12**, 321 (1958).
2. P. A. S. Smith, *The Chemistry of Open Chain Nitrogen Compounds*, Vol. II, Chapt. 13. Benjamin, New York (1966).
3. J. H. Boyer, in *The Chemistry of Nitro and Nitroso Groups*, edited by H. Feuer, Part 1, p. 215. Wiley, New York (1968).
4. G. Sandler and H. Kara, in *Organic Preparations of Functional* Groups, edited by A. Blomquist, Vol. 12, Part II. Academic Press, New York (1971).
5. D. L. H. Williams, *Nitrosation*. Cambridge University Press, Cambridge (1987).
6. M. Azoulay, B. Stymne and G. Wettermark, *Tetrahedron* **32**, 2961 (1976).
7. M. Azoulay and E. Fischer, *J. Chem. Soc., Perkin Trans. 2* 637 (1982).
8. K. G. Orrell, V. Šik and D. Stephenson, *Magn. Reson. Chem.* **25**, 1007 (1987).
9. M. Azoulay, R. Lippman and G. Wettermark, *J. Chem. Soc., Perkin Trans. 2* 256 (1981).
10. P. A. S. Smith, *The Chemistry of Open Chain Nitrogen Compounds*, Vol. II, Chapt. 13, p. 360. Benjamin, New York (1966).
11. P. Kabasakalian and E. R. Townley, *J. Am. Chem. Soc.* **84**, 2711 (1962).
12. D. L. Hammick, W. A. M. Illingworth and F. R. Snell, *J. Chem. Soc.* 671 (1933).
13. G. H. Coleman, C. M. McCloskey and F. A. Stuart, *Org. Synth.* **25**, 80 (1945).
14. D. A. Dieterich, I. C. Paul and D. Y. Curtin, *J. Am. Chem. Soc.* **96**, 6372 (1974).
15. E. W. Abel, T. P. J. Coston, K. G. Orrell, V. Šik and D. Stephenson, *J. Magn. Reson.* **70**, 34 (1986).
16. R. Willem, *Prog. Nucl. Magn. Reson. Spectrosc.*, edited by J. W. Emsley, J. Feeney and L. H. Sutcliffe, Pergamon Press, Oxford, **20**, 1 (1987).
17. C. Wynants, G. Van Binst, C. Mügge, K. Jurkschat, A. Tzschach, H. Pepermans, M. Gielen and R. Willem, *Organometallics* **4**, 1906 (1985).
18. R. C. Weast (Editor), *Handbook of Chemistry and Physics*, 62nd ed., p. A-37. Chemical Rubber Co., Cleveland, Ohio (1981–82).