plexes. This kind of adduct was, up until now, only proposed,^[7] but not observed experimentally.

Addition of solutions of 1,3,5-tris(*N*-piperidyl)benzene (1), 1,3,5-tris(*N*-morpholinyl)benzene (2), or 1,3,5-tris(*N*-pyrrolidinyl)benzene (3) in CD_2Cl_2 to a solution of DNBF in CD_2Cl_2 at -70 °C in an NMR tube resulted in the signals of the starting materials in the ¹H NMR spectra disappearing and the appearance of new signals, which are ascribed to compounds 4, 5, and 6 (Scheme 1). Acidification of solutions of 4 in [D₆]DMSO by addition of DCl afforded a spectrum containing exclusively the signals of the starting materials, namely 1 (in a protonated form) and DNBF.

Reactive Intermediates

Evidence for Carbon–Carbon Meisenheimer– Wheland Complexes between Superelectrophilic and Supernucleophilic Carbon Reagents**

Carla Boga, Erminia Del Vecchio, Luciano Forlani,* Andrea Mazzanti, and Paolo E. Todesco

The observation, or the isolation (when it is possible), of intermediates in nucleophilic aromatic substitution^[1a] (S_NAr; the so-called Meisenheimer complexes M) and in electrophilic aromatic substitution^[1b,c] (the so-called Wheland complexes W) reactions is an important confirmation of the proposed mechanisms. Our interest has, in the past, focused on intermediates in the S_NAr reaction^[2] and, more recently, also on electrophilic aromatic substitution reactions^[3] (Wheland intermediates). Both kinds of σ complexes (M and W) have appreciable stability when a number of strong electronwithdrawing groups or electron-donating groups, respectively, are present on the aromatic ring. 4,6-Dinitrobenzofuroxan (DNBF) is a powerful carbon electrophilic reagent^[4] and 1,3,5-tris(N,N-dialkylamino)benzenes are powerful carbon nucleophilic reagents.^[5] Herein, we report that these couples act as superelectrophilic^[6,7] and supernucleophilic reagents, thus providing evidence of a carbon-carbon coupling reaction with formation of Meisenheimer-Wheland zwitterionic com-

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Scheme 1. Reaction of 1,3,5-tris (*N*,*N*-dialkylamino) benzenes with 4,6-dinitrobenzofuroxan to produce carbon–carbon zwitterionic complexes.

ŃO₂

DNBF

NR₂ = N-piperidyl

NR₂ = N-morpholinyl

 $NR_2 = N$ -pyrrolidinyl

5

6

NR₂

NR₂

NR₂ = N-piperidyl

 $NR_2 = N$ -morpholinyl

NR₂ = N-pyrrolidiny

0,

2

3

Scheme 1 illustrates the observed reactions with formation of Wheland–Meisenheimer complexes **4–6**, whose structures are in agreement with the spectral data obtained at low temperature. Detailed analyses of the reaction products **4–6** by variable-temperature NMR spectroscopy revealed an unexpected behavior of these W–M compounds which deserves some special consideration. We describe herein the study carried out on compound **6** in detail; similar behavior was obtained with **4** and **5** (full spectral data for compounds **4– 6** are shown in Tables 1 and 2).

The mixing of cooled $(-70 \,^{\circ}\text{C})$ solutions of DNBF and 1,3,5-tris(*N*-pyrrolidinyl)benzene (**3**) in CD₂Cl₂ afforded a new product (**6**) immediately. The ¹H NMR spectrum of this solution (maintained at $-70 \,^{\circ}\text{C}$) shows four separate signals in the range $\delta = 4.3-5.1$ ppm, three of which correspond to the three hydrogen atoms belonging to the tris(*N*-pyrrolidinyl)-benzene moiety and one ascribed to the furoxanic ring. The other hydrogen atom, which is hydrogen bonded to the furoxanic ring, was found at $\delta = 8.60$ ppm (Table 1).

Direct proton to carbon correlation (gHSQC sequence, Figure 1, left) obtained at -70 °C shows that two of the four hydrogen atoms which resonate at $\delta = 4.61$ and 4.43 ppm are connected to two carbon atoms at $\delta = 87.22$ and 88.28 ppm; these chemical shifts are in the range typical for sp²hybridized carbon atoms of 1,3,5-tris(*N*-pyrrolidinyl)benzene. In contrast, the two remaining proton signals ($\delta = 4.32$ and 5.00 ppm) are connected directly to carbon atoms resonating at $\delta = 45.09$ and 40.87 ppm, respectively, which is clear evidence for the sp³ hybridization of these carbon atoms.

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Table 1: ¹ H NMR spectral data in CD ₂ Cl ₂ .										
Compound	T [°C]	$\delta_{ extsf{H5}}$	$\delta_{ m H7}$	$\delta_{ extsf{H10}}$	$\delta_{\rm H12}{}^{\rm [a]}$	$\delta_{\rm H14}{}^{\rm [a]}$	$\delta_{\rm NCH_2}$	$\delta_{ m others\ CH_2}$		
1	+25			6.00			3.00-3.10	1.60–1.70 (m, 12H),		
							(m, 12H)	1.46–1.56 (m, 6H)		
2	+25			6.00			3.05-3.10	3.75-3.82 (m, 12H)		
							(m, 12H)			
3	+25			5.18			3.19-3.27	1.88–1.98 (m, 12H)		
							(m, 12H)			
DNBF	+25	9.11 (d, <i>J</i> = 1.9 Hz)	8.84 (d, J=1.9 Hz)							
4	-70	8.77	4.97 (d, J=4.7 Hz)	4.68 (d, J=4.7 Hz)	5.26	5.11	2.70-4.25	1.30–1.95 (m, 18H)		
							(m, 12H)			
4	+ 25	8.78	5.15	5.22 ^[b]	5.22 ^[b]	5.22 ^[b]	3.28-3.52	1.60–1.80 (m, 18H)		
							(m, 12H)			
5	-70	8.81	5.05 (d, J = 3.8 Hz)	4.66	5.16	5.30		2.85–4.25 (m, 24 H)		
5	-25	8.83	5.30	5.23 ^[b]	5.23 ^[b]	5.23 ^[b]		3.10-4.00 (m, 24 H)		
6	-70	8.60	5.00 (d, J=3.6 Hz)	4.32 (d, J=3.6 Hz)	4.61	4.43	2.70-4.25	1.60–2.20 (m, 12H)		
							(m, 12H)			
6	+25	8.67 (d, J=0.9 Hz)	5.14	4.58 ^[b]	4.58 ^[b]	4.58 ^[b]	3.15-3.60	1.80–2.15 (m, 12H)		
							(m, 12H)			

[a] Interchangeable assignments. [b] Broad singlet.

Proton to proton correlation obtained at -70 °C (gCOSY sequence, Figure 1, right) shows that the signal at $\delta = 5.00$ ppm is correlated with the furoxanic hydrogen atom at $\delta = 8.60$ ppm and to one of the three tris(*N*-pyrrolidinyl)benzene hydrogen atoms at $\delta = 4.32$ ppm (J = 3.6 Hz).



Figure 1. Left: gHSQC spectrum of compound **6** in CD_2Cl_2 at -70 °C. Right: gCOSY spectrum of compound **6** in CD_2Cl_2 at -70 °C.

All the mentioned NMR data, recorded at -70 °C, agree with a Wheland–Meisenheimer (W–M) structure that is produced in the reaction between DNBF and tris(*N*-pyrrolidinyl)benzene.^[8]

In the Wheland–Meisenheimer structure (Scheme 1) C12 and C14 are sp² hybridized, while C10 and C7 are sp³ hybridized, thus accounting for the two high-field ¹³C NMR signals at $\delta = 45.09$ and 40.87 ppm, respectively. The presence of two distinct hydrogen (and carbon) signals for the two other CH groups (C12 and C14) of the tris(*N*-pyrrolidinyl)benzene can be easily explained because of the presence of an asymmetric carbon center (C7) and a "C₂ center" (C10);^[9] under these conditions the two CH atoms are diastereotopic and thus appear as anisochronous signals in both the ¹H and ¹³C NMR spectra. The same effect can be observed for the aromatic quaternary carbon atoms, which show three separated signals, and for the pyrrolidinic rings (six signals for the six α -nitrogen carbon atoms).

On raising the temperature, neither the ¹³C nor ¹H NMR spectra change until -30 °C (-30 °C and -40 °C for 4 and 5, respectively). Above -30 °C the three signals ascribed to the hydrogen atoms of the tris(*N*-pyrrolidinyl)benzene moiety show line broadening as a result of an exchange process. The signals coalesce at -1 °C and appear as a single signal at +20 °C (Figure 2). In contrast, the other signal (H7) always remains sharp.

It is worth noting that the dynamic process observed is reversible: warming the solution from -30 °C to room temperature and cooling again to -30 °C gives a spectrum that is identical to the starting one. Satisfactory line-shape simulation (Figure 2) was obtained using only one rate constant, which shows that ΔG^+ is not constant with temperature and indicates that the ΔS^+ value is not negligible. An accurate analysis by means of the Eyring equation^[10] yields $\Delta H^+ = 22.7 \pm 0.2 \text{ kcal mol}^{-1}$ and $\Delta S^{\pm=}32 \pm 5 \text{ e.u.}$ for **6** ($\Delta H^+ =$ $17.6 \pm 0.2 \text{ kcal mol}^{-1}$, $\Delta S^{\pm=}18 \pm 6 \text{ e.u.}$ for **4** and $\Delta H^+ = 10.4 \pm$ 0.3 kcal mol}^{-1}, $\Delta S^{\pm=}10 \pm 6 \text{ e.u.}$ for **5**).

The same dynamic process can also be observed in the ¹³C NMR spectra: the coalescence of the three quaternary carbon atoms C11, C13, and C15 can be clearly seen above -30 °C, and they appear as a single line above -1 °C. However, the coalescence and the single averaged line cannot be observed for the three carbon atoms at $\delta = 87.22$, 88.28, and 45.09 ppm because of the very large chemical shift difference between the signals (a line width of about 3 KHz is expected assuming $\Delta G^{+} \approx 13$ kcal mol⁻¹ at room temperature). As in the proton spectra, the fourth signal, belonging to the C7 atom of the furoxanic ring, is always sharp irrespective of the temperature.



Comp.	<i>T</i> [°C]	$\delta_{\rm C4,C6,C8,C9}{}^{[a]}$	$\delta_{ ext{cs}}$	$\delta_{ ext{c7}}$	$\delta_{ ext{C10}}$	$\delta_{ ext{C12,C14}}{}^{[a]}$	$\delta_{ ext{C11,C13,C15}}^{[a]}$	$\delta_{ m NCH_2}$	$\delta_{ m NCH_2CH_2}$ and NCH2CH2CH2
1	+25				99.32	99.32, 99.32	154.80	52.15	25.29, 26.94
2	+25				97.64	97.64, 97.64	154.06	50.72	67.69
3	+25				86.67	86.67, 86.67	150.67	48.46	26.12
DNBF	+25	116.65, 138.46, 145.19, 151.19	126.42	120.14					
4	-70	109.61, 113.43, 119.28, 150.43	135.47	41.99	39.47	88.24, 90.09	158.51, 159.85, 159.89	48.33, 48.76 49.08, 49.80(2 sig. ov.), 49.85	23.78, 24.22, 24.26, 24.56, 24.88, 26.15, 26.26, 26.51, 27.33
4	+25	110.92, 114.21, 120.00, 151.21	135.70	43.75			160.34	50.44	26.53, 24.72
5	-70	109.44, 113.44, 118.34, 150.33	135.51	42.94	39.17	89.52, 91.23	159.87, 160.27, 160.94	46.75, 47.36, 47.60, 47.90, 48.37, 48.71	65.00, 65.56, 66.12, 66.20, 66.56, 66.97
6	-70	109.36, 113.62, 119.16, 150.95	133.78	40.87	45.09	87.22, 88.28	154.91, 155.29, 157.94	47.54, 48.37, 48.86, 49.03, 49.37, 49.55	24.83, 24.97, 25.01, 25.43, 25.88, 26.17
6	+25	110.25, 114.54, 119.46, 151.79	134.60	42.28			157.86 ^[b]	49.79	25.96

Table 2: ¹³C NMR spectral data in CD₂Cl₂.

[a] Interchangeable assignments. [b] Broad signals.

ature, thus showing that the furoxanic anion is still present at room temperature.^[11]

Hence, the dynamic NMR data suggest the existence, above the coalescence temperature, of a Wheland–Meisenheimer complex in three homomeric structures (Scheme 2) with bonds C7/C10, C7/C12, and C7/C14 rapidly exchanging. The positive value of ΔS^{\pm} also agrees with a mechanism in which a bond involved in the W–M complex is broken. It should be noted that the activation parameters obtained for **6** are quite different from those obtained for **4** and **5**. A

possible explanation can be hypothesized by considering the different steric environments involved in the W–M complexes: although the steric effects of the six-membered rings are almost the same in **4** and **5**, the smaller and more flexible five-membered rings in **6** lead to a stabilization of the W–M structure and hence affords greater ΔH^{\dagger} and ΔS^{\dagger} values.

The existence of a π - π charge-transfer (CT) complex between DNBF and tris(amino)benzene derivatives could also occur, but experimental spectral data obtained for

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Figure 2. Left: experimental variable-temperature NMR spectra of 6. Right: line-shape simulation obtained with the rate constant indicated. $NR_2 = piperidyl$, morpholinyl, pyrrolidinyl.



Scheme 2. Proposed interconversion pathway for the observed reversible and temperature-dependent transformation of W–M structures **4–6**.

compounds **4** and **6** clearly show (also at room temperature) the presence of sp³ hybridization at the C7-position of the DNBF moiety (¹³C NMR signal at $\delta = 40.87$ ppm). If such a CT complex existed, this carbon atom should revert back to sp² hybridization and hence a ¹³C NMR signal at around $\delta = 90$ ppm would be observed in the ¹³C NMR spectrum at +25°C.

In conclusion, the reaction between a superelectrophilic reagent such as DNBF and powerful carbon nucleophilic reagents such as 1,3,5-tris(N,N-dialkylamino)benzenes have given the possibility to characterize, for the first time,

zwitterionic carbon–carbon Meisenheimer–Wheland complexes, whose structures were ascertained by one- and twodimensional NMR experiments. A dynamic NMR study of these species also showed, through observation of coalescence, that increasing the temperature results in the formation of a Wheland–Meisenheimer complex in three homomeric structures with bonds C7/C10, C7/C12, and C7/C14 rapidly exchanging. Very strongly activated systems often give unexpected results, and this is the case here.

Experimental Section

Compounds 1 and 2 were prepared as reported in ref. [3]. Compound 3 was prepared in a similar manner from 1,3,5-trichlorobenzene and pyrrolidine. DNBF was prepared as reported in ref. [8]. NMR spectra were recorded on Varian Gemini 300, Mercury 400, or Inova 600 spectrometers operating at 300, 400, or 600 MHz (for ¹H NMR) or 75.46, 100.56, or 150.80 MHz (for ¹³C NMR), respectively. Signal multiplicities were established by DEPT experiments. Chemical shifts were referenced to the solvent [(δ = 5.30 and 54.2 ppm for CD₂Cl₂), $(\delta = 7.27 \text{ and } 77.0 \text{ ppm for CDCl}_3)$, $(\delta = 2.0 \text{ and } 0.3 \text{ ppm for CD}_3\text{CN})$, $(\delta = 2.6 \text{ and } 39.5 \text{ ppm for } [D_6]DMSO)$ for ¹H and ¹³C NMR, respectively]. The variable-temperature NMR spectra and 2D lowtemperature spectra were recorded on the Inova 600 with a direct PFG Probe. The temperatures were calibrated by substituting the sample with a precision Cu/Ni thermocouple before the measurements. Complete fitting of dynamic NMR line shapes was carried out using a PC version of the DNMR-6 program.^[12]

The low-temperature samples for NMR experiments were prepared directly in the NMR tube by mixing two cooled $(-70^{\circ}C)$ solutions of DNBF (0.006 M) and **1**, **2**, or **3** (0.006 M) in CD₂Cl₂.

The behavior observed for compounds 4-6 on changing the temperature and the reversibility of the process was also observed in CDCl₃ solutions.

Mixing 1, 2, or 3 with DNBF in acetonitrile at low temperature $(-30 \,^{\circ}\text{C})$ resulted in the precipitation of a coral-red solid. Heating the resulting solids, which were isolated by filtration, in a melting point apparatus resulted in them gradually darkening (133–140 $^{\circ}$ C, 118–125 $^{\circ}$ C, and 129–135 $^{\circ}$ C for compounds 4–6, respectively) then decomposing. However, their ¹H and ¹³C NMR spectra were identical to those obtained for compounds 4–6, formed directly in an NMR tube and recorded at 25 $^{\circ}$ C.

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