PERKIN 2

# The analogy between C=O and C(CN)$_2$. Part 2.[1] Structural properties of *N,N*-dialkylaminobenzamides and the analogously substituted 2-(phenylmethylene)propanedinitriles

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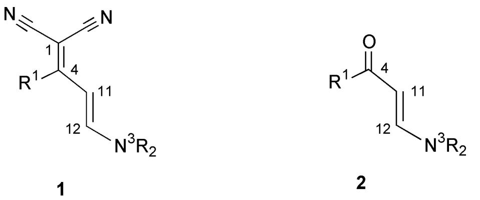
The barrier to rotation around the carbon amino nitrogen bond in 2-[*N,N*-dimethylamino(phenyl)methylene]-propanedinitrile (**4a**), 2-[*N,N*-diethylamino(phenyl)methylene]propanedinitrile (**4b**), 2-[(phenyl)pyrrolidin-1-yl-methylene]propanedinitrile (**4c**), *N,N*-dimethylbenzamide (**5a**), *N,N*-diethylbenzamide (**5b**) and (phenyl)pyrrolidin-1-ylmethanone (**5c**) were determined using dynamic $^1$H NMR spectroscopy. X-Ray crystal structures of **4a**, **4b**, **4c** and **5a** were determined, and quantum chemical calculations were carried out for **4a** and **5a** and for the transition structures for the rotation process of these two compounds. The barriers were generally lower than for the vinyl analogues **1** and **2**. Although the calculated transition structures for **4a** and **5a** indicate some steric strain, the reduction of the barriers, especially for series **4**, indicates that steric strain is more important in the ground state, thus raising its energy relatively more than for the transition state.

## Introduction

A few years ago we reported on the analogy in structural properties of 4-(*N,N*-dialkylamino)-1,1-dicyanobuta-1,3-dienes (**1**) and 3-(*N,N*-dialkylamino)propenones (**2**) as studied by dynamic $^1$H NMR, X-ray crystallography and quantum chemical calculations on model compounds (Chart 1).[1]



**1** **2**

**Chart 1** **a**: R$^1$ = phenyl, R = Me; **b**: R$^1$ = phenyl, R = Et; **c**: R$^1$ = phenyl, R$_2$ = (CH$_2$)$_4$, atom numbering according to crystal structures.

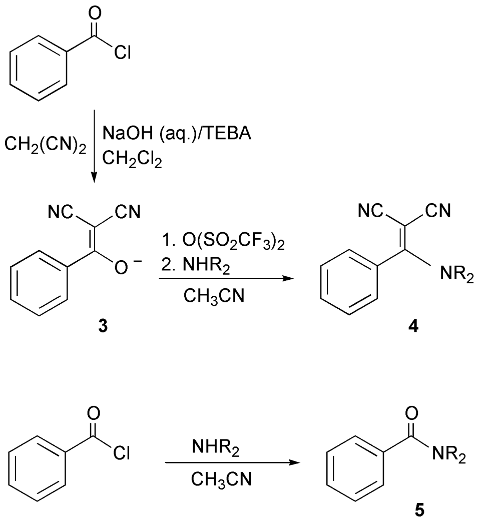
Two important experimental results were obtained from these studies. Firstly, the barriers to rotation around the C12–N3 bond were almost identical within each series (≈ ±1.0 kJ mol$^{-1}$), but the barriers in **2** were about 10 kJ mol$^{-1}$ lower than in series **1**, indicating that the conjugation along the chain N3–C1(O1) was more efficient in the latter series. This reduction of the barriers to rotation in series **2** relatively to **1** is also corroborated by the crystal structure determinations. The N3–C12 bond lengths are ≈0.01 Å longer and the C11–C12 bond lengths are ≈0.01 Å shorter for series **2** than the corresponding bond lengths in series **1**, as expected if the conjugation is more effective in the latter series. These trends were also indicated by the quantum chemical calculations.

Secondly, the lack of variations of the bond lengths and the barriers to rotations by changing the amino alkylating groups indicates that steric effects involving these groups are of minor importance in both series. It then became interesting to see how removal of the intermittent atoms C11 and C12 would affect the structural properties as studied above. Therefore the lower vinyl analogues 2-[*N,N*-dialkylamino(phenyl)methylene]-propanedinitriles **4** and *N,N*-dialkylbenzamides **5** were synthesised and investigated by dynamic $^1$H NMR, X-ray single crystal structure determination and quantum chemical calculations.

## Results and discussion

### Preparation of 4 and 5

The synthesis of the benzamides **5** was straight forward from benzoyl chloride, while the 2-substituted propanedinitriles **4** were made *via* the triflate (trifluoromethanesulfonate) as described in detail in the Experimental section (Scheme 1).



**Scheme 1** Synthetic routes to **4** and **5**.

### Dynamic $^1$H NMR

The results of our determinations of the barriers to rotation for the various substituted **4** and **5** are entered in Table 1. We found it sufficient for our purpose to use the simplified method of determining the coalescence temperature $T_c$ together with the peak separation at slow exchange ($\Delta\nu$) to estimate the barrier using the well known equation [eqn. (1)[2]].

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**Table 1** Dynamic $^1$H NMR results for compounds **4** and **5** studied in *N*,*N*-dimethylformamide-d$_7$, 0.1 molar solution

| Cpd. | $T_{c(\alpha)}{}^a$/K | $\Delta G^{\#}{}_{(\alpha)}{}^{a,b}$ | $\Delta\nu^c$/Hz | $\nu_{1/2}{}^c$/Hz | $T_{c(\beta)}{}^a$/K | $\Delta G^{\#}{}_{(\beta)}{}^{a,b}$ | $\Delta\nu^c$/Hz | $\nu_{1/2}{}^c$/Hz | Ref. values$^b$ |
|---|---|---|---|---|---|---|---|---|---|
| **4a** | 330 | 64.9 ± 1.0 | 178.9 | 2.9 | | | | | |
| **4b** | 328 | 63.6 ± 1.0 | 225.8 | 4.0 | 321 | 64.3 ± 1.0 | 105.0 | 3.7 | |
| **4c** | 380 | 74.3 ± 1.0 | 220.2 | 2.8 | 365 | 74.4 ± 1.0 | 77.2 | 2.1 | |
| **5a** | 299 | 64.1 ± 1.0 | 18.5 | 1.3 | | | | | $CDCl_3$: 64.4,[3a] 65.4,[3b] 65.5,[3c] 65.6,[3d] 66.0[3e]<br>$CD_3CN$: 63.5,[3a] 64.8[3d]<br>$CD_3OD$: 67.8[3e] |
| **5b** | 304 | 61.5 ± 1.0 | 77.5 | 3.1 | 291 | 61.8 ± 1.0 | 23.6 | 2.1 | $CDCl_3$: 62.3[3f]<br>$CD_3CN$: 60.6,[3f] 62.6[3g] |
| **5c** | 324 | 69.1 ± 1.0 | 23.2 | 3.3 | n.f.$^d$ | | | | Not reported |

[a] α = $NCH_3/NCH_2$–; β = –$CH_2$–/–$CH_3$. [b] In kJ mol$^{-1}$. [c] $\Delta\nu$, peak separation at slow exchange; $\nu_{1/2}$, averaged line width at slow exchange. [d] Not found due to small $\Delta\nu$.

**Table 2** Reduction in the barrier to rotation by removal of the C=C double bond in compounds **1** and **2** ($\Delta\Delta G^{\#}$)$^a$

| | Compound | | | | | |
|---|---|---|---|---|---|---|
| | **1a–4a** | **1b–4b** | **1c–4c** | **2a–5a** | **2b–5b** | **2c–5c** |
| Difference | 9.0 | 11.9 | 1.4 | −0.4 | 4.4 | −3.5 |

[a] In kJ mol$^{-1}$. Barriers for **1** and **2** are taken from ref. 1.

$$\Delta G^{\ddagger} = RT_c\,[23 + \ln T_c/\Delta\nu] \qquad (1)$$

The estimated barriers to rotation for the benzamides **5a** and **5b** (Table 1) correspond very well to those reported in the literature,[3] especially taking into account the expected solvent effect.[3c,3d,3f] As mentioned in the introduction the barriers to rotation were nearly identical within each series **1** and **2**. This is not the situation within series **4** and **5** where the values for the barriers are quite scattered (Table 1). The obvious reason for these differences must be of steric nature since the amino groups in the latter two series are much closer to the rest of the molecule. The steric requirement for the three amino substituents should be: methyl ≤ pyrrolidine < ethyl. The effect of removal of the C=C bond on the barriers to rotation is given in Table 2.

The process of rotation around the C–N bond is symmetrical from one planar ground state to the other, and somewhere along the route the amino nitrogen should be pyramidal where resonance interaction with the X-group is minimised. If in the transition state the phenyl is coplanar to the $C(CN)_2$ or C=O groups, conjugation is reestablished as shown in Fig. 1.

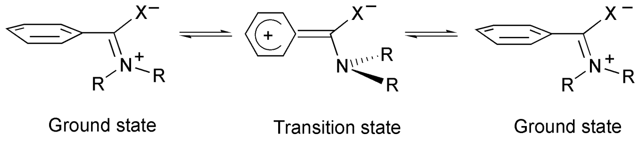

**Fig. 1** Process of rotation around the C–N bond in **4** and **5**.

The reduction of the barriers to rotation for **4** and **5** relative to series **1** and **2** (except **2c**–**5c**) as shown in Table 2 can be interpretated as steric hindrance in the ground state where the amino substituents are in the same plane as the X-group. This strain is released in or near the transition state where the amino nitrogen has pyramidal configuration. This indicates that the transition state energy is influenced less by the change in structure going from series **1** to **4** and **2** to **5**, and that the ground state energy for the compounds with ethyl substituents suffers the largest change. Somewhat surprising is the large difference between the methyl and pyrrolidine substituents in propanedinitrile analogues, perhaps due to the freedom of rotation for the methyl groups. The much smaller reduction of the barriers for the oxygen analogues is certainly as expected as oxygen and the propanedinitrile group have completely different spatial requirements.

## Crystal structures

Unfortunately, only **5a** of the amides was crystalline above room temperature, a single crystal X-ray structure could be obtained. ORTEP plots of structures **4a**, **4b**, **4c**, and **5a** are presented in Fig. 2.

Selected structural data are given in Table 3 and dihedral angles between nearly planar moieties are given in Table 4.

Some disorder was present in **4c** where another conformer of the five-membered ring is present in an amount of 25%. Data for this conformer are disregarded. The crystal structures for **4a**, **4b**, **4c**, and **5a** indicate complete planarity along the X–N3 chain (X = $C(CN)_2$), O–N1 chain for amide **5a**, including the first carbon atoms of the substituents at the amino nitrogen. The phenyl group is almost perpendicular to this chain and to the propanedinitrile group for the ethyl (**4b**) and pyrrolidine (**4c**) compounds, and for the other two compounds (**4a** and **5a**) the dihedral angles (Table 4) are too high to account for any conjugation effect between the phenyl group and the X-group (O or $C(CN)_2$). This absence of conjugation is corroborated by the C4–C5 bond length (≈1.495 for cpds. **4** and 1.504 for **5a**).[4] These bonds and the C1–C4 bonds in **4** and the C4–O1 bond in **5a** are almost identical with those in series **1** and **2**,[1] and C1–C4 in **4** are much longer than a formal double bond.

The single bonds to the cyano groups for compounds **4** are identical with the corresponding bonds in compounds **1**,[1] as are the CN triple bonds, indicating that the electron withdrawing effect of the cyano groups is inductive and that they do not contribute in a resonance manner.[5]

## Quantum chemical calculations

Previous experience has shown us that the B3LYP/6–31G(d) method is adequate for the purpose of estimating rotational barriers in compounds of this type.[1] In contrast to HF and MP2 with the same basis set, B3LYP provides estimates of the barriers in good accord with experiment. We found that the calculated free energies of activation are approximately 10 kJ mol$^{-1}$ lower than the corresponding experimental numbers. One reason for the slight discrepancy is probably that the calculations are conducted for the compound *in vacuo*, while the experiments are carried out in solution.

The results of the present calculations are shown in Fig. 3 and 4 and Table 5. The structural parameters optimised for **4a** and **5a** are in excellent agreement with the X-ray crystallographic data. It is evident that both structures are sterically congested in the neighbourhood of the amide bond. According to the calculations the phenyl groups are 52 and 40 degrees out of the C–C=C (**4a**) and C–C=O (**5a**) planes, respectively, *cf.* Table 4. In addition, the $C{=}C(CN)_2$ group is twisted by 20 degrees relative to the $N(CH_3)_2$ group. The implications of these steric interactions is that full double bond conjugation cannot

**Table 3** Selected structural data for **4a**, **4b**, **4c**, and **5a**

| | Bond lengths/Å | | | |
|---|---|---|---|---|
| | **4a** | **4b** | **4c** | **5a** |
| C4–C5 | 1.492(2) | 1.497(1) | 1.497(1) | 1.504(1) |
| C1(O1)–C4 | 1.399(2) | 1.406(1) | 1.403(1) | 1.242(1) |
| C4–N3(N1 **5a**) | 1.338(2) | 1.331(1) | 1.306(3) | 1.351(1) |
| N3(N1 **5a**)–C11 | 1.465(2) | 1.474(1) | 1.489(4) | 1.456(1) |
| N3–(C12 **4a**),(C13 **4b**),(C14 **4c**),(N1–C12 **5a**) | 1.470(2) | 1.477(1) | 1.468(7) | 1.457(1) |
| C1–C2 | 1.433(2) | 1.426(1) | 1.424(1) | |
| C1–C3 | 1.428(2) | 1.426(1) | 1.426(1) | |
| N1–C2 | 1.151(2) | 1.161(1) | 1.160(1) | |
| N2–C3 | 1.152(2) | 1.164(1) | 1.160(1) | |
| | Bond angles/° | | | |
| C1(O1)–C4–C5 | 117.8(1) | 115.0(1) | 117.8(1) | 119.2(1) |
| C1(O1)–C4–N3(N1 **5a**) | 123.6(1) | 126.9(1) | 126.3(1) | 122.0(1) |
| C5–C4–N3(N1 **5a**) | 118.6(1) | 118.1(1) | 115.8(1) | 118.8(1) |
| | Torsion angles/° | | | |
| C1(O1)–C4–C5–C6 | −122.1(1) | −90.8(1) | −87.9(1) | −125.7(1) |
| C1(O1)–C4–N3(N1 **5a**)–C11 | 16.2(2) | 3.9(1) | −2.9(4) | 2.8(1) |
| C1–C4–N3–(C12 **4a**),(C13 **4b**),(C14 **4c**),O1–C4–N1–C12a (**5a**) | −160.4(1) | −178.1(1) | −178.5(3) | −165.1(1) |

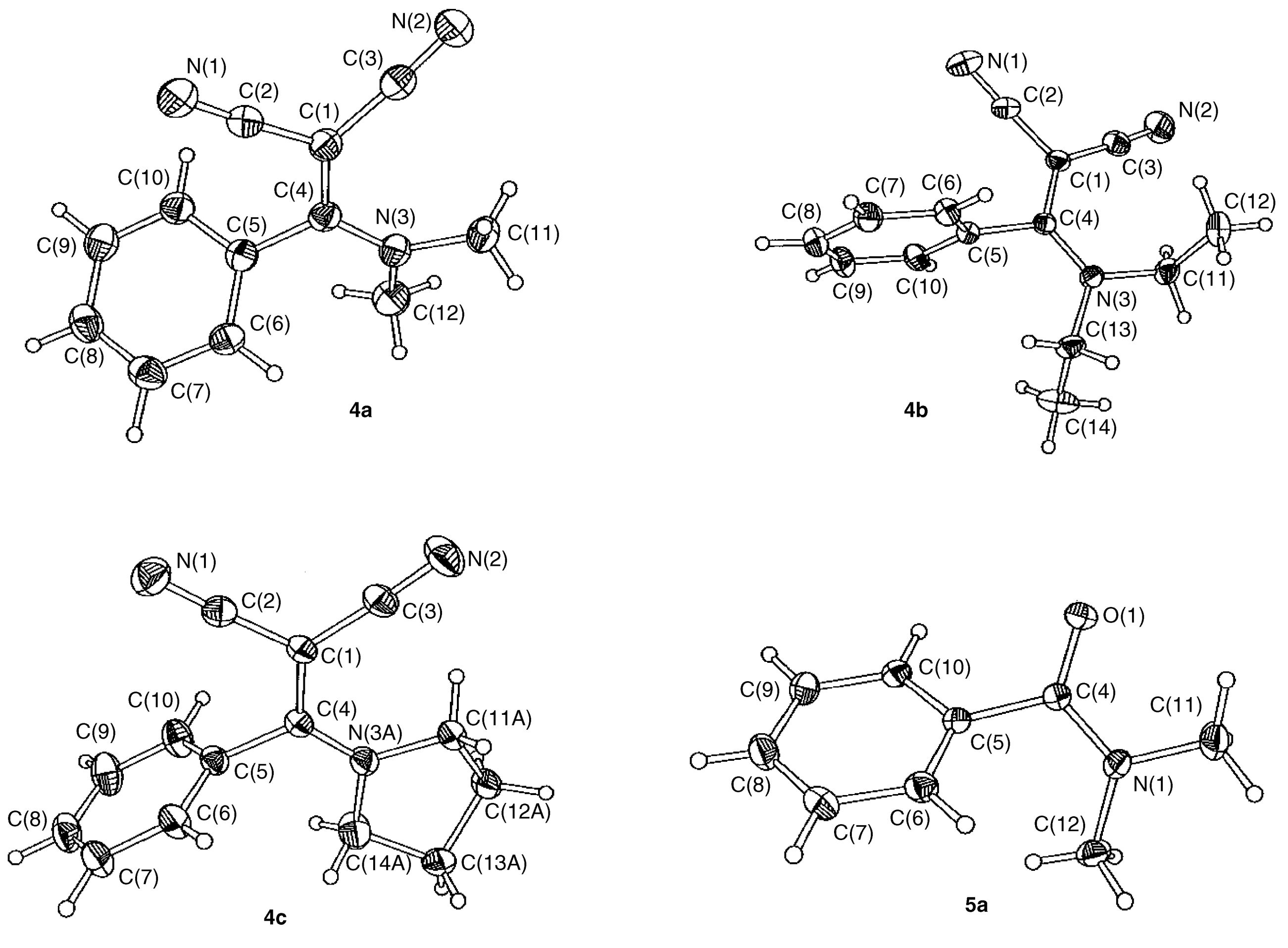

**Fig. 2** ORTEP plots of **4a**, **4b**, **4c** and **5a**. Ellipsoids are shown at 50% probability. For **4c** only the main conformer is shown.

be achieved in any of the two compounds, and the propanedinitrile **4a** appears to be more severely affected than the ketone **5a**.

According to the B3LYP calculations the two rotational barriers are 53 (65) and 51 (64) kJ mol$^{-1}$ (experimental value in parenthesis). Similar differences were also found for the vinyl analogues **1** and **2**.[1] This could be due to a solvent effect caused by a more effective solvatisation of the ground state in the rotation process, perhaps caused by a larger charge separation in this state. Calculations of the dipole moments support such a proposal (Table 6).

Upon C–N bond rotation to achieve the transition structures (**TS-4a** and **TS-5a**, respectively), we have observed several interesting structural features. Both transition structures have a

**Table 4** Dihedral angles (°) between nearly planar moieties[a]

| | Dihedral angle | | | |
|---|---|---|---|---|
| | **4a** | **4b** | **4c** | **5a** |
| 1–2 | 67.2 | 88.5 | 86.0 | 58.9 |
| 1–3 | 59.5 | 88.9 | 88.1 | 45.8 |
| 2–3 | 33.8 | 12.1 | 2.2 | 9.0 |

[a] Plane 1, phenyl; plane 2, C4–NCC (the carbon atoms directly bonded to N); plane 3, propanedinitrile group (**5a**: line C–O).

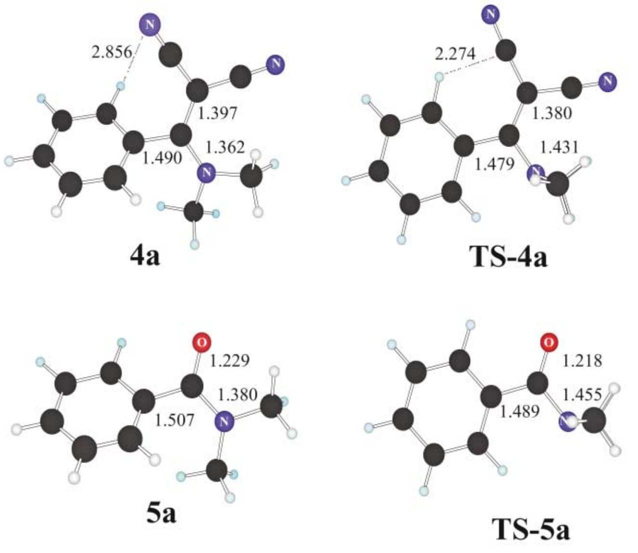

**Fig. 3** Structural parameters for **4a**, **TS-4a**, **5a** and **TS-5a** as obtained by quantum chemical calculations.

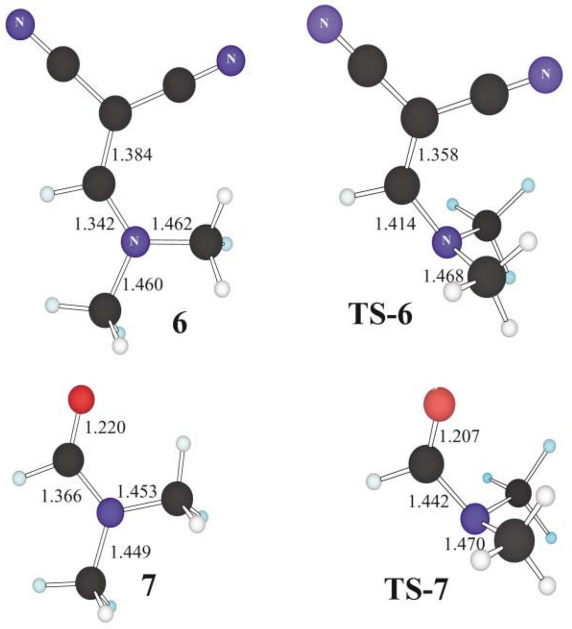

**Fig. 4** Structural parameters for **6**, **TS-6**, **7** and **TS-7** as obtained by quantum chemical calculations.

**Table 5** Energies from the quantum chemical calculations (B3LYP/6-31G(d))

| Structure | $E^a$ | $G^b$ | $\Delta G^c$ |
|---|---|---|---|
| **4a** | −627.897914 | −627.939209 | 0 |
| **TS-4a** | −627.879005 | −627.919210 | 52.5 |
| **5a** | −479.380411 | −479.416872 | 0 |
| **TS-5a** | −479.362719 | −479.397497 | 50.9 |
| **6** | −396.929303 | −396.965462 | 0 |
| **TS-6** | −396.900558 | −396.934592 | 81.1 |
| **7** | −248.409183 | −248.438262 | 0 |
| **TS-7** | −248.374623 | −248.402896 | 92.9 |

[a] Absolute energy at 0 K in Hartrees including zero point vibrational energies. [b] Absolute Gibbs free energy at 298 K in Hartrees. [c] Relative Gibbs free energies in kJ mol$^{-1}$.

**Table 6** Calculated dipole moments for ground and transition structures for **4a** and **5a**

| | Compound | | | |
|---|---|---|---|---|
| | **4a** | **TS-4a** | **5a** | **TS-5a** |
| $\mu$/Debye | 8.47 | 6.18 | 3.42 | 2.12 |

plane of symmetry, meaning that the N(CH$_3$)$_2$ moiety is perfectly perpendicular to the plane which consists of the rest of the molecule. This allows for the phenyl groups to achieve in-plane double bond conjugation with the respective double bond (C=C(CN)$_2$ or C=O). However, a perpendicular transition structure does not relieve steric strain by necessity. It is evident from the indicated nonbonded contacts, that this is far from being the case. As a consequence it is difficult to judge to what degree electronic or steric effects are responsible for the similar barriers in the two compounds. In the conjugated systems studied previously by us[1] (Chart 1) rotation of the C–N bond in the ketone requires less energy than in the propanedinitrile. If the electronic effect was transferable from the previous system to the present, this would indicate that the transition structure is less sterically hindered than the minimum energy structure in the case of the propanedinitrile.

To investigate this further, we performed calculations for the analogous compounds **6** and **7**, where the phenyl group is substituted by hydrogen. It is highly interesting that for this pair, the keto has a higher barrier for rotation than the propanedinitrile. It therefore seems to be the case that the steric hindrance of **TS-4a** is stronger than in **TS-5a**, since the electronic effects affecting barrier heights should be rather similar. The calculated barriers for **6** and **7** are in good agreement with the experimental values which are determined to be ≈75[6] and ≈86 kJ mol$^{-1}$,[7] respectively.

## Experimental

### General

Mps were measured on a Reichert Thermopan (Wien) apparatus and are uncorrected. Infrared spectra were recorded on a Nicolet Magna 550 FTIR spectrometer using an attenuated total reflectance (ATR) ZnSe-plate for solid samples (unless otherwise noted). High-resolution NMR spectra ($^1$H and $^{13}$C) were obtained using Bruker Spectrospin Avance DMX 200 and DMX 300 spectrometers where the reference compound SiMe$_4$ is software controlled; *J*-values are given in Hz. Ultraviolet spectra were recorded using a Shimadzu UV-260 spectrophotometer, and mass spectra were obtained using a Micromass Instrument ProSpec Q. Where dry conditions were required, commercial solvents (FLUKA's brand), dried to a water content < 0.01%, stored under nitrogen over Molecular Sieve, were used.

### Materials

The sodium salt of 2-[hydroxy(phenyl)methylene]propanedinitrile (**3**) was prepared according to a slightly modified literature procedure.[8] Benzoyl chloride (4.50 g, 32.5 mmol) and malononitrile (2.12 g, 32.5 mmol) were dissolved in dichloromethane (50 ml) and cooled to 0 °C.

Benzyltriethylammonium chloride (TEBA, 0.75 g) in a 10 M solution of NaOH (7.5 ml) was added dropwise while stirring. After 15 minutes the precipitated solid was filtered off and washed with dichloromethane (3 times) and diethyl ether (3 times) and dried in a desiccator giving 5.9 g of **3**, white powder (94%). $\nu_{max}$/cm$^{-1}$: 2210s (CN), 1527s, 1375s. $\delta_H$(acetone-$d_6$): 7.3–7.4 (3 H, m), 7.6–7.7 (2 H, m). Spectroscopic data are in accordance with literature values for the protonated salt.[8]

2-[*N,N*-Dimethylamino(phenyl)methylene]propanedinitrile (**4a**), 2-[*N,N*-diethylamino(phenyl)methylene]propanedinitrile (**4b**), and 2-[(phenyl)pyrrolidin-1-ylmethylene]propanedinitrile (**4c**): the triflate of the above salt (**3**) was prepared according to a literature procedure.[9] To a solution of the sodium enolate (2.00 g, 10.4 mmol for **4a** and 0.53 g, 2.8 mmol for **4b** and **4c**) in acetonitrile (65 ml for **4a** and 20 ml for **4b** and **4c**) was added trifluoromethanesulfonic anhydride (3.74 g, 2.19 ml, 10.4 mmol for **4a** and 0.99 g, 0.58 ml, 2.8 mmol for **4b** and **4c**), and the mixture was refluxed for 2 hours and cooled to room temperature.

Dimethylamine (4.69 g, 104 mmol in 10 ml acetonitrile), diethylamine (2.56 g, 35.0 mmol), or pyrrolidine (2.49 g, 35.0 mmol), was added as appropriate. After one hour, diethyl ether was added and the mixture was washed with NaCl solution, dried with $MgSO_4$, and evaporated under reduced pressure. The crude product was dissolved in dichloromethane and filtered through a short $SiO_2$ column. Recrystallization from chloroform–pentane yielded 1.5 g **4a**, white crystals (63%), 0.13 g **4b**, white crystals (21%), and 0.22 g **4c**, light yellow crystals (22%).

**2-[*N,N*-Dimethylamino(phenyl)methylene]propanedinitrile (4a).** Mp 121–122 °C. $\nu_{max}$/cm$^{-1}$: 2204s (CN), 2191m (CN). $\delta_H$(CDCl$_3$): 2.12 (3 H, br), 2.83 (3 H, br), 7.3–7.4 (2 H, m), 7.4–7.5 (3 H, m). $\delta_C$(CDCl$_3$): 43.0, 44.2, 52.7, 116.6, 117.2, 128.4, 129.2, 131.6, 132.8, 171.5. MS (EI, 70 eV): *m*/*z* 197 (100%, M$^{+\bullet}$), 196 (92, [M − H]$^+$), 156 (24). HRMS: Found: 197.095281, $C_{12}H_{11}N_3$requires 197.095297 (0.1 ppm), 198.098859, $C_{11}{}^{13}CH_{11}N_3$ requires 198.098652 (−1.0 ppm).

**2-[*N,N*-Diethylamino(phenyl)methylene]propanedinitrile (4b).** Mp 96–97 °C. $\nu_{max}$/cm$^{-1}$: 2206s (CN), 2193m (CN). $\delta_H$(CDCl$_3$): 1.02 (3 H, br), 1.40 (3 H, br), 3.09 (2 H, br), 3.84 (2 H, br), 7.2–7.3 (2 H, m), 7.4–7.5 (3 H, m). $\delta_C$(CDCl$_3$): 13.7, 45.0, 48.6, 52.2, 116.5, 117.2, 127.4, 129.1, 130.8, 133.7, 169.0. MS (EI, 70 eV): *m*/*z* 225 (100%, M$^{+\bullet}$), 224 (53, [M − H]$^+$), 210 (35, [M − CH$_3$]$^+$), 196 (43, [M − CH$_2$CH$_3$]$^+$). HRMS: Found: 225.126692, $C_{14}H_{15}N_3$ requires 225.126598 (−0.4 ppm), 226.129710, $C_{13}{}^{13}CH_{15}N_3$ requires 226.129952 (1.1 ppm).

**2-[(Phenyl)pyrrolidin-1-ylmethylene]propanedinitrile (4c).** Mp 199–199.5 °C. $\nu_{max}$/cm$^{-1}$: 2206m (CN), 2192m (CN), 1549s. $\delta_H$(CDCl$_3$): 1.7–1.8 (2 H, m), 2.0–2.1 (2 H, m), 3.15 (2 H, t, $^3J$ = 6.8), 4.00 (2 H, t, $^3J$ = 6.9), 7.2–7.3 (2 H, m), 7.4–7.5 (3 H, m). $\delta_C$(CDCl$_3$): 24.5, 25.8, 50.7, 51.7, 53.9, 117.1, 117.3, 127.0, 129.2, 130.7, 134.0, 167.4. MS (EI, 70 eV): *m*/*z* 223 (100%, M$^{+\bullet}$), 222 (40, [M − H]$^+$), 195 (25). HRMS: Found: 223.110748, $C_{14}H_{13}N_3$ requires 223.110948 (0.9 ppm), 224.113308, $C_{13}{}^{13}CH_{13}N_3$ requires 224.114302 (4.4 ppm).

***N,N*-Dimethylbenzamide (5a), *N,N*-diethylbenzamide (5b), and phenylpyrrolidine-1-ylmethanone (5c).** Benzoyl chloride was allowed to react with the appropriate amine in acetonitrile giving amines **5a**, **5b**, and **5c** in good yields. Spectroscopic data as expected for all three compounds.

### NMR measurements

Variable-temperature $^1$H NMR spectra were obtained using a Bruker Avance DMX 300 spectrometer. The probe temperature was calibrated using a digital microprocessor thermometer HD 9219 with Pt 100 sensor (DELTA OHM, 35030 Caselle di Selvazzano, Italy).

### X-Ray crystallographic analysis data for compounds 4a, 4b, 4c and 5a

X-Ray data were collected on a Siemens SMART CCD diffractometer[10] using graphite monochromated Mo-Kα radiation.† Data collection method: ω-scan, range 0.6°, crystal to detector distance 5 cm. Data reduction and cell determination was carried out with the SAINT and XPREP programs.[10] Absorption corrections were applied by the use of the SADABS program.[11]

The structure was determined and refined using the SHELXTL program package.[12] The non-hydrogen atoms were refined with anisotropic thermal parameters; hydrogen positions were located from difference Fourier maps and given isotropic thermal parameters.

**Crystal data for compound 4a.** $C_{12}H_{11}N_3$, $M$ = 197.24, monoclinic, $P2_1$, $a$ = 7.139(1), $b$ = 7.955(1), $c$ = 9.407(1) Å, $\beta$ = 96.85(1)°, $V$ = 530.43(6) Å$^3$, $Z$ = 2, $D_x$ = 1.235 Mg m$^{-3}$, $\mu$ = 0.077mm$^{-1}$, $T$ = 150(2) K, measured 5791 reflections in the $\theta$ range 5.1–26.4°, $R_{int}$ = 0.027. 180 parameters refined against 2096 $F^2$, $R1$ = 0.029 and $wR2$ = 0.070 for $I_o > 2\sigma(I_o)$ and $R1$ = 0.033 and $wR2$ = 0.072 for all data.

**Crystal data for compound 4b.** $C_{14}H_{15}N_3$, $M$ = 225.29, monoclinic, $P2_1/c$, $a$ = 9.883(1), $b$ = 14.454(1), $c$ = 8.915(1) Å, $\beta$ = 95.36(1)°, $V$ = 1267.96(5) Å$^3$, $Z$ = 4, $D_x$ = 1.180 Mg m$^{-3}$, $\mu$ = 0.072 mm$^{-1}$, $T$ = 150(2) K, measured 17827 reflections in the $\theta$ range 2.1–37.8°, $R_{int}$ = 0.018. 214 parameters refined against 4430 $F^2$, $R1$ = 0.047 and $wR2$ = 0.107 for $I_o > 2\sigma(I_o)$ and $R1$ = 0.067 and $wR2$ = 0.141 for all data.

**Crystal data for compound 4c.** $C_{14}H_{13}N_3$, $M$ = 223.27, monoclinic, $P2_1/c$, $a$ = 8.458(1), $b$ = 14.199(1), $c$ = 10.533(1) Å, $\beta$ = 109.56(1)°, $V$ = 1192.0(2) Å$^3$, $Z$ = 4, $D_x$ = 1.244 Mg m$^{-3}$, $\mu$ = 0.076mm$^{-1}$, $T$ = 150(2) K, measured 24533 reflections in the $\theta$ range 2.1–4.2°, $R_{int}$ = 0.025. 235 parameters refined against 7112 $F^2$, $R1$ = 0.054 and $wR2$ = 0.147 for $I_o > 2\sigma(I_o)$ and $R1$ = 0.073 and $wR2$ = 0.166 for all data.

**Crystal data for compound 5a.** $C_9H_{11}NO$, $M$ = 149.19, orthorhombic, $P2_12_12_1$, $a$ = 6.631(1), $b$ = 7.652(1), $c$ = 16.303(1) Å, $V$ = 827.21(11) Å$^3$, $Z$ = 4, $D_x$ = 1.198 Mg m$^{-3}$, $\mu$ = 0.079 mm$^{-1}$, $T$ = 150(2) K, measured 16518 reflections in the $\theta$ range 8.2–40.0°, $R_{int}$ = 0.030. 144 parameters refined against 4831 $F^2$, $R1$ = 0.040 and $wR2$ = 0.103 for $I_o > 2\sigma(I_o)$ and $R1$ = 0.046 and $wR2$ = 0.109 for all data.

### Theoretical methods

The program suite GAUSSIAN 98[13] was employed for all quantum chemical calculations. The hybrid density functional theory method according to Becke[14] incorporating the 6-31G(d) basis set (B3LYP/6–31G(d))[15] was used. All stationary points were subject to complete geometry optimisation. The optimised structures were checked for the correct number of negative eigenvalues of the Hessian (the second derivative matrix). Analytical force constants were computed at this stage and the vibrational frequencies were obtained together with the rotational constants. These molecular parameters were used within the framework of the rigid rotor/harmonic-oscillator approximation to calculate the absolute energies and Gibbs free energies. Zero point vibrational energies were not corrected.

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† CCDC reference numbers 168509–168512. See http://www.rsc.org/suppdata/p2/b1/b105532c/ for crystallographic files in .cif or other electronic format.

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