

Synthesis and Solid-State Structures of Alkyl-Substituted 3-Cyano-2-pyridones

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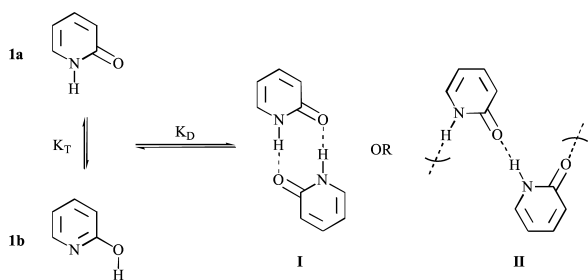
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A series of 3-cyano-pyridones carrying a variety of alkyl substituents at C-5 and C-6 has been synthesized and their solid-state structures have been studied. Hydrogen bonding interactions between individual pyridone molecules lead either to the formation of symmetric dimers of the $R_2^2(8)$ type or to helical chains of the C(4) type. Based on known and calculated structures for the 2-pyridone parent system, the solid-state structures can be divided in two groups representing cases with little external influence on the hydrogen bonding array (group A) and those with a larger external influence (group B).

Key words: Hydrogen Bonds, Dimerization, Solid State Structure, Aggregation, Alkylation

Introduction

2-Pyridone **1** and its derivatives have been studied extensively in the past few decades as prototype systems for bifunctional molecules. The *cis*-amide substructure present in 2-pyridones provides an ideal basis for building supramolecular structures and also for bifunctional catalysis [1–9]. The parent system **1**, which has been studied most frequently in the past, is known to exist in either the 2-pyridone (**1a**) or 2-hydroxypyridine (**1b**) tautomeric form, depending on the surrounding medium (Scheme 1) [10, 11]. Both tautomeric forms are known to readily aggregate. In particular in apolar solution, the symmetric dimer **I** (a $R_2^2(8)$ system) [12] as well as the chain motive **II** (a C(4) system) [12] being two conceivable oligomeric forms that are in equilibrium with the monomers **1a** and **1b** (Scheme 1).



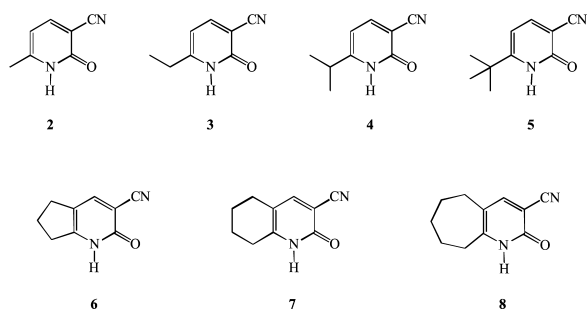
Scheme 1.

In analogy to the nucleic acid base pairs one expects the symmetrical dimer (**I**) as the most relevant dimer structure. This expectation is encouraged by recent gas phase and solution phase studies. Spectroscopic studies by Pratt and coworkers confirm a C_{2h} symmetric dimer in the gas phase with the parameters $r(N\cdots O) = 2.75 \pm 0.03 \text{ \AA}$ and $a(C=O\cdots H) = 122 \pm 2^\circ$ [13]. These results are supported by numerous theoretical studies of the gas phase dimer at a variety of theoretical levels, and values of $r(N\cdots O) = 2.768 \text{ \AA}$ and $a(C=O\cdots(H)-N) = 123.2^\circ$ are predicted at the B3LYP/6-311++G(2d,2p) level of theory [14]. These calculations also arrive at a dimerization energy of $-22.62 \pm 0.07 \text{ kcal/mol}$ at the CBS/MP2 level of theory. In the liquid phase the tautomeric equilibrium is influenced by the choice of the solvent favoring 2-pyridone **1a** in polar solvents [10, 15]. The aggregation behavior has been studied quantitatively by UV/vis measurements in cyclohexane and decane [10], by IR techniques in CCl_4 [16], by vapor pressure osmometry in chloroform [17], and by 1H NMR spectroscopy in $[D_8]$ -THF [15] and deuteriochloroform [18]. All of these studies are in clear support of a dimer structure in the particular solvent and thus in the liquid phase.

In contrast to the aggregation behavior of **1a** in the gas phase and the liquid state stands the solid state structure featuring chain structure **II** (Scheme 1)

Crystal Data	2	3	4	5	6	7	8
Molecular formula	C ₇ H ₆ N ₂ O	C ₈ H ₈ N ₂ O	C ₉ H ₁₀ N ₂ O	C ₁₀ H ₁₂ N ₂ O	C ₉ H ₈ N ₂ O	C ₁₀ H ₁₀ N ₂ O	C ₁₁ H ₁₂ N ₂ O
Formula weight	134.14	148.18	162.19	176.22	160.18	174.20	188.23
Crystal system	monoclinic	monoclinic	monoclinic	triclinic	triclinic	monoclinic	monoclinic
Space group	<i>P</i> 2 ₁ / <i>c</i>	<i>C</i> 2/ <i>c</i>	<i>P</i> 2 ₁ / <i>n</i>	<i>P</i> $\bar{1}$	<i>P</i> $\bar{1}$	<i>P</i> 2 ₁ / <i>n</i>	<i>P</i> 2 ₁ / <i>n</i>
<i>a</i> , <i>b</i> , <i>c</i> [Å]	3.981 (1) 7.302 (2) 21.832 (3)	21.877 (4) 9.874 (1) 7.189 (4)	10.740 (6) 6.930 (5) 12.131 (7)	7.956 (2) 10.616 (2) 12.854 (2)	4.192 (1) 8.076 (2) 11.679 (2)	5.965 (1) 16.487 (4) 9.301 (1)	9.955 (2) 5.665 (1) 16.841 (4)
α , β , γ [°]	90 91.48 (2) 90	90 95.96 (3) 90	90 110.53 (5) 90	93.35 (1) 100.65 (2) 102.69 (2)	80.97 (2) 84.48 (1) 84.13 (1)	90 105.17 (2) 90	90 93.27 (2) 90
Volume [Å ³]	634.5 (3)	1544.5 (9)	845.5 (9)	1035.4 (3)	387.2 (1)	882.8 (3)	948.2 (3)
<i>T</i> [K]	295	295	295	295	295	295	295
<i>Z</i>	4	8	4	4	2	4	4
μ [mm ⁻¹]	0.098	0.087	0.086	0.075	0.093	0.087	0.087
Reflections							
measured	2216	1242	1391	3504	1067	1465	1587
unique	1001	1209	1314	3240	911	1378	1491
obs ($\geq 2\sigma(I)$)	712	723	873	2327	748	1002	1194
<i>R</i> 1	0.0505	0.0636	0.0717	0.0484	0.0428	0.0532	0.0405
<i>wR</i> 2	0.1136	0.1674	0.1721	0.1189	0.1252	0.1208	0.1019
Goodness of fit	1.182	1.048	1.252	1.081	1.049	1.156	1.166

Table 1. Crystal data and structure refinement for the series of alkylated 3-cyano-2-pyridones **2–8** crystallized from CHCl₃/MeOH [19].



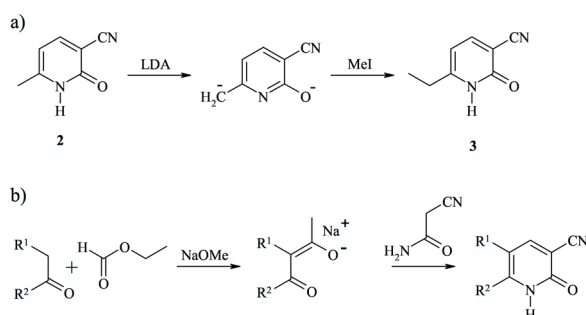
Scheme 2.

[4–6]. Here we show for a family of closely related 3-cyano-2-pyridones (**2–8** [19], Scheme 2) that both aggregation motives **I** and **II** occur in the solid state, even though structural variations of the substrates are rather minor and restricted to the “soft segment” alkyl portion of the systems [20].

Results

Synthesis

Compounds **2–8** (Scheme 2) have been synthesized following established synthetic procedures. For the synthesis of compound **2** we followed the procedure described by Binovi *et al.* [21]. The approach developed by Boatman *et al.* [22] was subsequently utilized to convert compound **2** to the 6-ethyl substituted system **3**. Our synthesis includes a modified deprotonation step using *in situ* generated LDA [23] and subse-



Scheme 3.

quent alkylation of the resulting dianionic intermediate with equimolar amounts of methyl iodide to afford **3** in 56% yield (Scheme 3a).

A general procedure for the synthesis of 3-cyano-2-pyridones functionalized at position C-5 and C-6 has been given by Paine (Scheme 3b) [24]. This approach is based on the condensation and cyclization of cyanoacetamide with 1,3-dicarbonyl compounds. The latter were synthesized *in situ* by a base-catalyzed formylation of adequate ketones to obtain the corresponding sodium salts. Following this sequence pyridones **2–8** were synthesized in good to acceptable yields. We were able to crystallize all compounds from chloroform/methanol solvent mixtures (1:1 *v/v*) to obtain crystals of suitable quality for X-ray structural analysis. The crystal data for pyridone derivatives **2–8** obtained under these conditions are summarized in Tables 1 and 2 [19].

Table 2. Selected structural data for compounds **1–8** [19]. Distances $r(X\text{--}Y)$ are given in Å, angles $a(X\text{--}Y\text{--}Z)$ are given in italic print and are measured in degrees.

Compound	1 ^a	2	2 ^b	3	4	5-A	5-B	6	7	8
Hydrogen bonding parameters										
$r(\text{N}\cdots\text{O})$	2.773	2.810	2.801	2.804	2.836	2.784	2.813	2.745	2.784	2.793
$r_{\text{A}}(\text{N}\text{--}\text{H})$	1.035	0.860	0.989	0.962	1.102	0.994	0.970	1.083	0.950	0.892
$r_{\text{B}}(\text{H}\cdots\text{O})$	1.778	1.953	1.815	1.853	1.745	1.804	1.865	1.670	1.835	1.901
$r(\text{NH}\cdots\text{HO})$	2.813	2.813	2.804	2.815	2.847	2.798	2.835	2.753	2.785	2.793
$a(\text{N}\text{--}\text{H}\cdots\text{O})$	<i>159.84</i>	<i>174.16</i>	<i>174.70</i>	<i>169.59</i>	<i>169.42</i>	<i>167.71</i>	<i>164.78</i>	<i>170.94</i>	<i>177.19</i>	<i>179.04</i>
$a(\text{C}=\text{O}\cdots\text{H})$	<i>134.70</i>	<i>123.27</i>	<i>122.63</i>	<i>129.53</i>	<i>140.07</i>	<i>135.28</i>	<i>136.64</i>	<i>118.44</i>	<i>124.71</i>	<i>124.68</i>
C\cdotsH and C\cdotsN contacts										
$r(\text{CN}\cdots\text{H}_{\text{p-aryl}})$	–	2.688	2.637	2.878	2.627	2.608	–	2.783	2.469	2.537
$a(\text{N}\cdots\text{H}\text{--}\text{C})$	–	<i>137.91</i>	<i>151.45</i>	<i>130.12</i>	<i>163.30</i>	<i>135.76</i>	–	<i>124.70</i>	<i>168.98</i>	<i>159.67</i>
								2.841		
								138.85		
$r(\text{N}\cdots\text{H}_{\text{alkyl}}\text{--}\text{C})$	–	Me-	Me-	Me-	Me-	5-H _B -	Me _A -	6-CH ₂ -	6-CH ₂ -	6-CH ₂ -
		2.716	2.682	2.918	2.860	2.735	2.787	3.089	2.675	2.824
$a(\text{N}\cdots\text{H}_{\text{alkyl}}\text{--}\text{C})$	–	Me-	Me-	Me-	Me-	5-H _B -	Me _A -	6-CH ₂ -	6-CH ₂ -	6-CH ₂ -
		<i>162.52</i>	<i>162.97</i>	<i>151.53</i>	<i>162.61</i>	<i>122.83</i>	<i>168.74</i>	<i>130.33</i>	<i>138.73</i>	<i>136.72</i>
$r(\text{O}\cdots\text{H}_{\text{alkyl}}\text{--}\text{C})$	3-CH-	Me-	Me-	Me-	7-CH-	Me-	Me-	7-CH ₂ -	7-CH ₂ -	9-CH ₂ -
	2.660	2.684	2.681	2.626	2.579	2.536	2.594	2.974	2.816	2.727
$a(\text{O}\cdots\text{H}_{\text{alkyl}}\text{--}\text{C})$	3-CH-	Me-	Me-	Me-	7-CH-	Me-	Me-	7-CH ₂ -	7-CH ₂ -	9-CH ₂ -
	<i>133.76</i>	<i>161.34</i>	<i>155.85</i>	<i>152.72</i>	<i>127.55</i>	<i>154.77</i>	<i>154.28</i>	<i>161.75</i>	<i>144.25</i>	<i>143.63</i>

^a Data from references [4–6]; ^b data from reference [25].

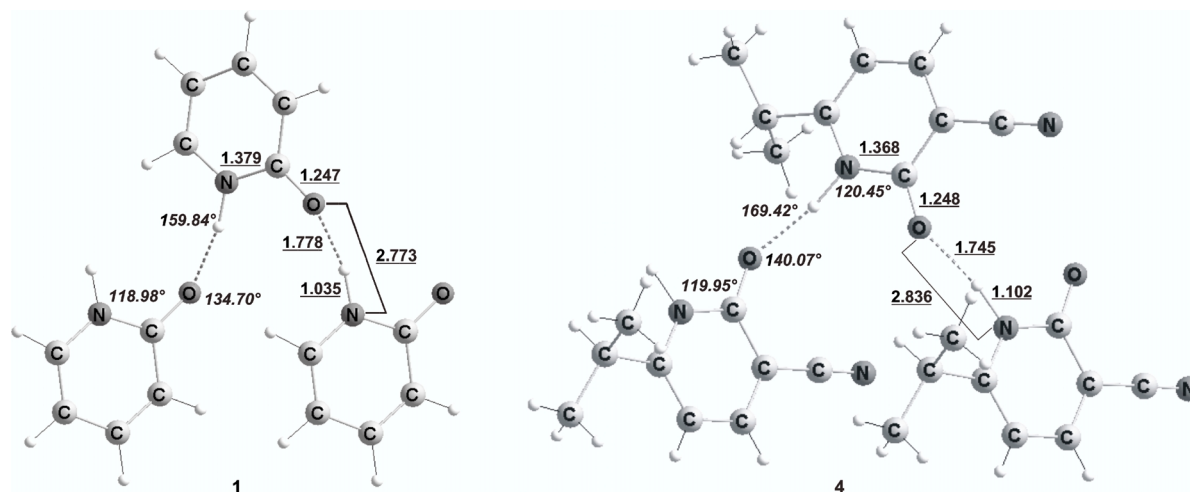


Fig. 1. Comparative illustration of compounds **1** and **4**, highlighting the chain forming hydrogen bridges. The hydrogen bonds are shown in dashed lines. Distances $r(X\text{--}Y)$ are underlined and angles $a(X\text{--}Y\text{--}Z)$ are given in italic print.

X-ray structures

2-Pyridone (1a): The comparative discussion of X-ray data starts with pyridone **1**, whose structure has been taken from Ohms *et al.* [5]. The key structural motive of the solid state structure of **1** is the arrangement of single pyridone molecules in helical chains, in which they are connected by alternating hydrogen

bonds. The most important hydrogen bonding parameters are $r(\text{N}\text{--}\text{H}\cdots\text{O}) = 2.813$ Å and $a(\text{C}=\text{O}\cdots\text{H}) = 134.70^\circ$. Due to difficulties in localizing the positions of the hydrogen atoms accurately, the $\text{N}\cdots\text{O}$ distance has most often been used in the past in analyzing hydrogen-bonding interactions. However, with larger deviations of the $\text{N}\text{--}\text{H}\cdots\text{O}$ fragment from linearity the direct $\text{N}\cdots\text{O}$ distance becomes less and less descriptive

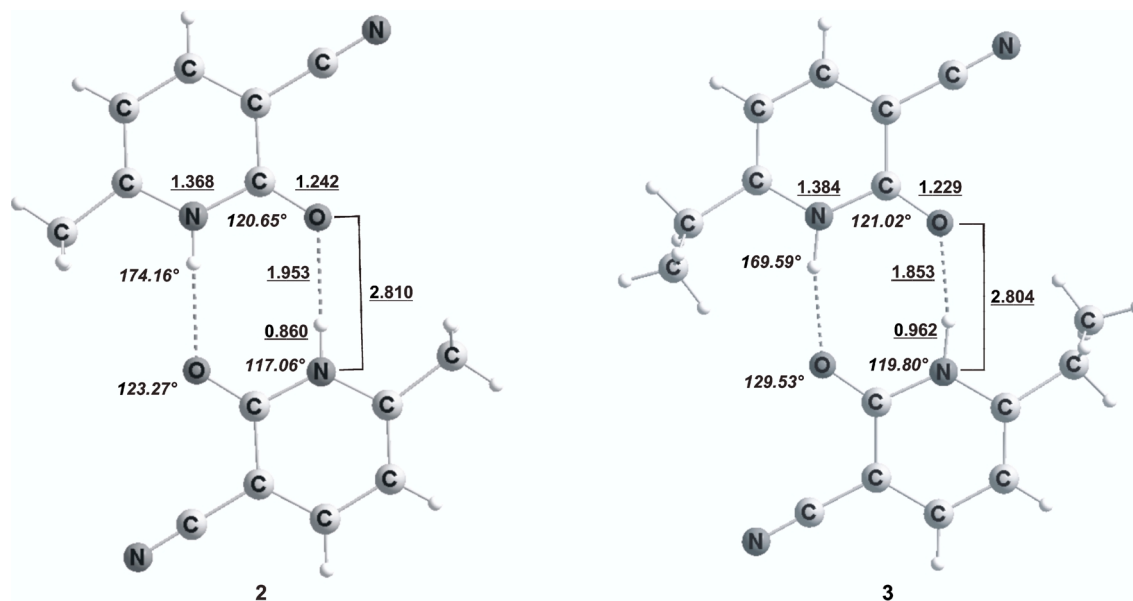


Fig. 2. X-ray crystal structure of the 6-methyl substituted pyridone **2** and the 6-ethyl derivative **3** showing the hydrogen bridged dimer in both cases. The hydrogen bonds are illustrated with dashed lines. Distances are given in Ångstrom and are underlined, angles in degrees and in italic print.

Table 3. Selected structural parameters for the gas phase dimers of **1**, **4**, and **6** as calculated at the B3LYP/6-311++G(2d,2p) level of theory. Distances $r(X-Y)$ are given in Å and angles $\alpha(X-Y-Z)$ in degrees.

Compound	1 _(C_{2v})	4 _(C_i)	6 _(C_i)
$r(N\cdots O)$	2.7684	2.7829	2.7614
$r_A(N-H)$	1.0389	1.0368	1.0397
$r_B(H\cdots O)$	1.7295	1.7463	1.7219
$r(NH+HO)$	2.7684	2.7830	2.7616
$\alpha(N-H\cdots O)$	179.95	178.84	178.57
$\alpha(C=O\cdots H)$	123.23	126.14	125.00

of the actual H-bonding process. We have therefore decided here to use the sum of $r(N-H)$ and $r(H\cdots O)$, abbreviated as $r(NH+HO)$, as a measure of the H-bonding distance (and thus efficiency).

It is interesting to compare the above parameters with those of the gas phase dimer featuring significantly shorter hydrogen bonds with $r(N-(H)\cdots O) = 2.75 \pm 0.03$ Å and more favorable hydrogen bonding angles at the carbonyl oxygen atom of $\alpha(C=O\cdots(H)-N) = 122 \pm 2^\circ$ [13]. While the hydrogen bond is essentially linear in the gas phase dimer, it is not in the solid state structure with $\alpha(N-H\cdots O) = 159.84^\circ$. Leutwyler and coworkers have shown that the structural parameters of the gas phase dimer can conveniently be reproduced by gas phase *ab initio* calculations (Table 3) at the Becke3LYP/6-311++G(2d,2p) level of theory [14].

6-Methyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (2) and *6-Ethyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (3)*: In contrast to **1**, both 6-methyl- and 6-ethyl substituted 3-cyano-pyridones **2** and **3** prefer the formation of a symmetric dimer in the solid state. The hydrogen bonding interactions are only slightly longer in these cases than in the gas phase dimer of **1** with $r(NH+HO) = 2.813$ Å (**2**) and 2.815 Å (**3**). The geometry of the hydrogen bond in the 6-methyl compound **2** is (compared to **1**) considerably closer to linearity ($\alpha(N-H\cdots O) = 174.16^\circ$) than in **3** where $\alpha(N-H\cdots O) = 169.6^\circ$. The hydrogen bonds connect to the carbonyl groups with $\alpha(C=O\cdots H) = 123.27^\circ$ (**2**) and $\alpha(C=O\cdots H) = 129.53^\circ$ (**3**). One remarkable feature found in the structure of **3** is the twisted arrangement of one dimer to the next one along the stacking axis, most likely in order to avoid collisions between the ethyl substituents. The structure of **2** is free of this complication and features regular stacks of dimers tilted along the stacking axis. For both **2** and **3** secondary contacts between the 3-CN substituents and the 4-H atoms of adjacent pyridone units exist and organize individual stacks to the overall solid-state structure. Similar observations were made by Munakata and coworkers [25]. They crystallized pyridone **2** from acetone and obtained a triclinic crystal structure. Despite these differences the symmetric

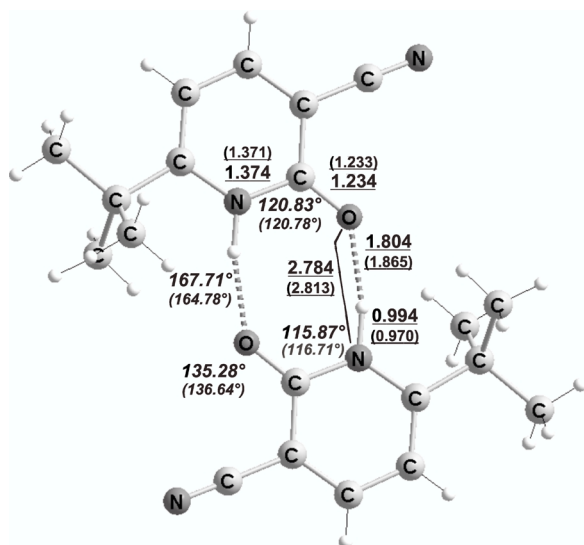


Fig. 3. X-ray crystal structure of compounds **5A** and **5B** showing the dimer motive. Hydrogen bonds are illustrated in dashed lines. Structural details for compound **5B** are given in parenthesis. Distances are given in Ångstrom and are underlined, angles in degrees and in italic print.

dimer reappears also in this case, again forming stacks of tilted dimers. The 3-CN \cdots 4-H interactions are also observable in this case, but lead to a slightly different overall structure. Another common feature of both solid-state structures of **2** and **3** is that the alkyl substituents orient themselves to form an apolar region between the polar hydrogen bonded dimers and cyano-CH-dimer arrangements.

6-Isopropyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (4): The key structural motive in compound **4** is the helical chain arrangement also found for

2-pyridone (**1a**). This arrangement is characterized by $r(\text{NH}\cdots\text{HO}) = 2.847 \text{ \AA}$, $a(\text{C}=\text{O}\cdots\text{H}) = 140.1^\circ$, and $a(\text{N}-\text{H}\cdots\text{O}) = 169.42^\circ$. The solid-state structure of **4** contains a parallel arrangement of independent helices, interconnected by secondary 3-CN \cdots 4-H and isopropyl \cdots isopropyl contacts (Fig. 1). The conformation of the isopropyl substituent is not symmetric with respect to the pyridone ring plane, but features one methyl group in an “axial” and one in an “equatorial” position (indicated by C-C-C-N torsion angles of $+74.3^\circ$ and -162.3° , respectively).

6-tert-Butyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (5): There are two different dimers in one unit cell of the 6-*tert*-butyl substituted pyridone **5**. Both species are arranged as single dimers connected by the double hydrogen bond motive forming two individual strands for **5A** and **5B**. Dimer **5A** is characterized by the parameters $r(\text{NH}\cdots\text{HO}) = 2.798 \text{ \AA}$ and $a(\text{C}=\text{O}\cdots\text{H}) = 135.28^\circ$, and dimer **5B** by the parameters $r(\text{NH}\cdots\text{HO}) = 2.835 \text{ \AA}$ and $a(\text{C}=\text{O}\cdots\text{H}) = 136.64^\circ$. Single dimers of type **5A** interconnect through 3-CN \cdots 4-CH contacts forming linear chains. The cyano groups in dimer **5B** maintain a secondary interaction to hydrogen atoms of the *t*-butyl group. The latter are oriented such that a U-shaped cavity is formed around the cyano substituents.

2-Oxo-1,5,6,7-tetrahydro-2H-1-pyridine-3-carbonitrile (6), **2-Oxo-1,2,5,6,7,8-hexahydro-quinoline-3-carbonitrile (7)** and **2-Oxo-1,5,6,7,8,9-hexahydro-2H-cyclohepta[b]pyridine-3-carbonitrile (8)**: The cyclopenta-annulated pyridone **6** also belongs to the dimer type with the following parameters $r(\text{NH}\cdots\text{HO}) = 2.753 \text{ \AA}$ and $a(\text{C}=\text{O}\cdots\text{H}) = 118.44^\circ$.

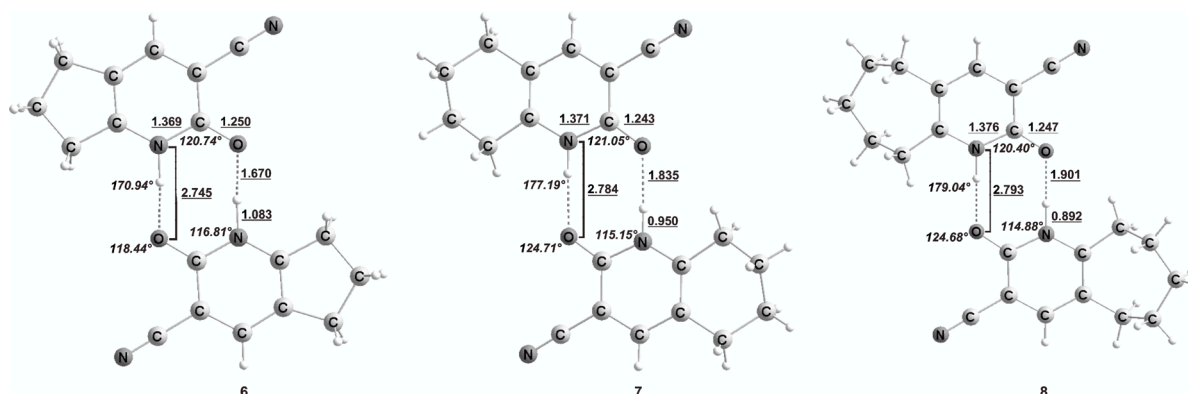


Fig. 4. X-ray crystal structures of compounds **6**, **7**, and **8**. The hydrogen bonds are illustrated with dashed lines. For each compound the hydrogen bridged dimer is shown. Distances are given in Ångstrom and are underlined, angles in degrees and in italic print.

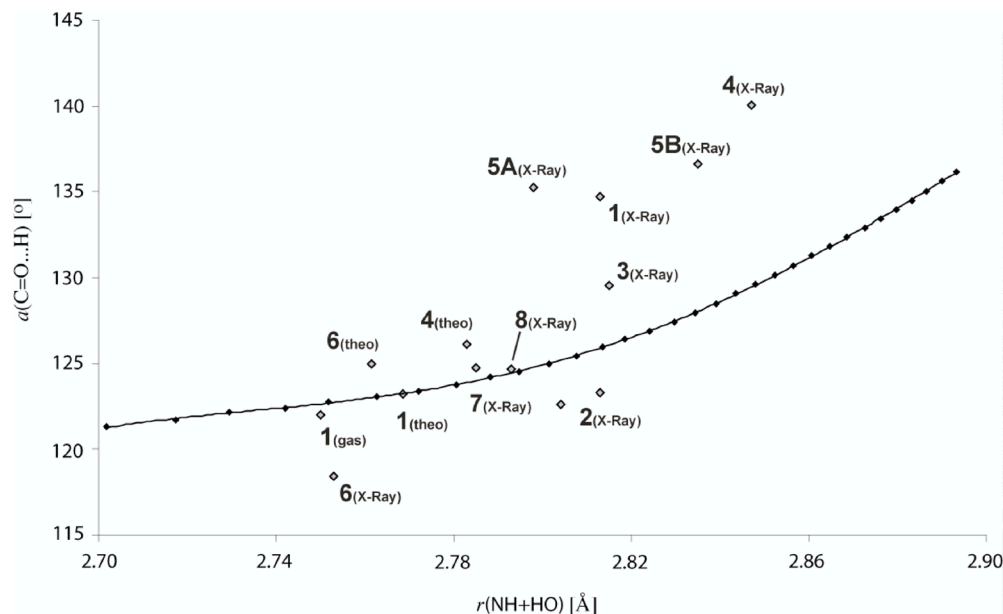


Fig. 5. Correlation of the hydrogen bond distance $r(\text{NH}+\text{HO})$ ($= r(\text{N}-\text{H}) + r(\text{H}\cdots\text{O})$, see Table 2) with the coordination angle $\alpha(\text{C}=\text{O}\cdots\text{H})$.

The hydrogen bridged dimers are interconnected through CN contacts of the 3-CN \cdots 4-H and 3-CN \cdots 4'-H type, forming an overall stair-like strand. The 5-membered ring in compound **6** has an almost planar conformation and orients itself in the solid state to form an unpolar gorge. Similar observations can be made for the crystal structure of compound **7**. There is also a hydrogen bridging interaction between two molecules of **7** forming symmetrical dimers with $r(\text{NH}+\text{HO}) = 2.785 \text{ \AA}$ and $\alpha(\text{C}=\text{O}\cdots\text{H}) = 124.71^\circ$. The six-membered aliphatic ring in **7** is slightly non-planar, flipping one methylene group above and one methylene group below the pyridone ring plane. Overall this leads to locally C_i symmetric dimers. Adjacent dimers are shifted relative to each other by one pyridone unit, forming infinite stacks of tilted dimer units. Secondary interactions between cyano groups and ring CH_2 -units interconnect individual stacks, forming overall stair-like patterns. Contacts between the unpolar alkyl groups appear to be somewhat more dominant in **7** than in **6**, again forming an unpolar gorge. The seven-membered ring derivative **8** shows a similar behavior in the crystal structure as the previously discussed compounds **6** and **7**. Again two molecules of **8** form a symmetrical dimer with $r(\text{NH}+\text{HO}) = 2.793 \text{ \AA}$ and $\alpha(\text{C}=\text{O}\cdots\text{H}) = 124.68^\circ$. The annelated 7-membered ring has a flat chair like conformation ex-

tending towards one side of the pyridone ring plane. This leads to locally C_i symmetric dimers. Individual dimers of **8** stack in the same fashion as already observed for **7**. Due to the increased size of the alkyl portion of **8** the unpolar gorge between individual stacks of dimers is now even more dominant than observed for **6** and **7**.

Discussion

From the above detailed discussion of structural data it is clear that three types of intermolecular interactions appear to exist in all systems **2–8**: (a) hydrogen bonding interactions between the pyridone carbonyl oxygen and the pyridone N-H group forming either cyclic dimers of the $R_2^2(8)$ type or helical chains of the $C(4)$ type; (b) interactions between the cyano nitrogen atom and hydrogen atoms located either at C4 of the pyridone ring or in the alkyl substituents; and (c) hydrophobic interactions between the alkyl substituents leading to the formation of unpolar channels in the solid state structure. Of these only the hydrogen bonding interactions will be discussed in some more detail, not only due to their strength but also due their importance in bifunctional catalysis [8,9]. Two of the more important hydrogen bonding parameters are depicted for all systems in Fig. 5, the distance $r(\text{NH}+\text{HO})$ and its correlation with the angle $\alpha(\text{C}=\text{O}\cdots\text{H})$.

In this graphical representation it becomes quite apparent that the gas phase (dimer) structure and the solid state (helical chain) structure of pyridone **1** differ considerably in both $r(\text{NH}+\text{HO})$ and $a(\text{C}=\text{O}\cdots\text{H})$. The gas phase (dimer) structure of **1** can closely be reproduced at the Becke3LYP/6-311++G(2d,2p) level of theory [14] and we can therefore explore the response of the dimer structure of **1** to distortive internal forces using constrained geometry optimizations. Stretching one of the hydrogen bonds in the dimer of **1** in a stepwise fashion and allowing all other structural parameters to relax yields the data points shown as filled dots and connected by a solid line. We may think of this line as "typical" for pyridones, which are not influenced by external forces. This point of view is supported by the results obtained in gas phase calculations on the dimers of pyridones **4** and **6** (Table 3). The $r(\text{NH}+\text{HO})$ and $a(\text{C}=\text{O}\cdots\text{H})$ parameters obtained for these systems are rather similar to those for **1** and one may therefore conclude that neither the 3-cyano substituent nor the alkyl substituents connected to C5 and C6 of the pyridone ring lead to fundamentally different hydrogen bonding parameters. This would imply that major deviations from the deformation line for **1** shown in Fig. 5 are indeed due to attractive or repulsive external forces. With respect to their solid state parameters $r(\text{NH}+\text{HO})$ and $a(\text{C}=\text{O}\cdots\text{H})$, we can approximately divide the systems **2–8** in two groups. Group A is located in close vicinity to or slightly below the deformation line of **1** and includes all those pyridones whose alkyl substituents do not extend significantly above or below the pyridone ring plane (**2, 6, 7, 8**). The shortest $r(\text{NH}+\text{HO})$ distances and the smallest coordination angle $a(\text{C}=\text{O}\cdots\text{H})$ in this group can be found for pyridone **6**. Group B is located above the deformation line of **1** and includes systems whose alkyl substituents extend significantly below or above the pyridone ring plane, such as **3** and **5A/5B**, but also the two systems **1** and **4** crystallizing in the helical chain structure. The most interesting candidate in this group B is pyridone **4** showing the longest $r(\text{NH}+\text{HO})$ distances and the largest coordination angle $a(\text{C}=\text{O}\cdots\text{H})$ of all systems studied here. That this is mainly the effect of external forces and not a consequence of internal compression through the 6-isopropyl substituent is made clear by comparison of the solid state structure of **4** with its (calculated) gas phase dimer. The latter is located in close vicinity to all other (calculated or measured) gas phase dimers, displaced to shorter $r(\text{NH}+\text{HO})$ distances and smaller co-

ordination angles $a(\text{C}=\text{O}\cdots\text{H})$ relative to the solid state structure of **4**.

Despite the fact that a rough correlation between the hydrogen bond distance $r(\text{NH}+\text{HO})$ and the coordination angle $a(\text{C}=\text{O}\cdots\text{H})$ appears to exist in the data shown in Fig. 5 (larger hydrogen bond distances corresponding to larger coordination angles), we have to acknowledge that the type of supramolecular structure present in the solid state cannot easily be predicted from the substitution pattern.

Conclusion

The *cis*-amide motive present in the 3-cyano-2-pyridones studied here provides the basis for the formation of two different supramolecular structures in the solid state. The formation of symmetrical dimers of the $R_2^2(8)$ type as well as helical chains of the C(4) type in the solid state structures of a family of closely related 3-cyano-2-pyridones implies that the *cis*-amide motive present in these systems does not lead to the formation of symmetric dimers with very high fidelity. What is a clear disadvantage for the rational design of solid state structures (crystal engineering), whose success depends on the predictable behavior of individual building blocks, may, however, be seen as an advantage in the area of supramolecular catalysis, in which recognition of the rather flexible transition states may be considered as one of the most important points [26].

Experimental Section

General: All necessary reagents were purchased from commercial sources and used without further purification, unless mentioned otherwise. Aliphatic and cyclic ketones, and ethyl formate were fractionally distilled and stored over molecular sieves. 2-Pyridone **1** was purchased from Aldrich, recrystallized from hexane, dried in vacuum and stored under N_2 . All air-sensitive reactions were carried out under a nitrogen atmosphere. THF and diethyl ether were distilled in a circulation apparatus from sodium-benzophenone under nitrogen. LDA solutions were prepared from diisopropylamine (DIPA), distilled and stored over molecular sieves, and commercially available *n*-butyllithium (Aldrich, 2.5 M in hexane) in THF at 0 °C immediately prior to use. Pyridones **3–8** were purified by flash chromatography on silica gel (40–63 mesh). R_f values were determined by thin layer chromatography (TLC) on commercial precoated silica gel 60 F₂₅₄ plates (0.25 mm, Merck). Visualization was accomplished with UV light at a wavelength of 254 or 366 nm. NMR spectra were recorded on a Bruker AMX 300 spectrometer (300.13 MHz (^1H) and 75.47 MHz (^{13}C)) and

Varian VXR 400 S spectrometer (399.98 MHz (^1H) and 100.57 MHz (^{13}C)). Chemical shifts are given as δ values in ppm relative to the applied deuterated solvent as the internal standard ($\text{CDCl}_3 = 7.24$ (^1H), $= 77.0$ (^{13}C), $[\text{D}_6]\text{-DMSO} = 2.49$ (^1H), $= 39.7$ (^{13}C)) and J values in Hz. Mass spectra were carried out using a FINIGAN MAT 90 and a FINIGAN MAT 95Q mass spectrometer operating in EI (electron impact) with an ionization energy of 70 eV. The UV/vis spectra were obtained with a Perkin-Elmer Lambda 16 spectrophotometer. The IR spectra were measured with a Perkin-Elmer 1420 Infrared Spectrometer as potassium bromide pellets. Microanalyses were performed by the microanalytical laboratory of the Department Chemie of the Ludwig-Maximilians-Universität München. Melting points were determined in a capillary tube in an Electrothermal IA 9000 SERIES apparatus and are uncorrected.

General procedures for the synthesis of 3-cyano-2-pyridone derivatives (for pyridones 4, 5, 6, 7, 8)

A: Preparation of the α -hydroxymethylene-ketone sodium salts [24]: A solution of sodium methoxide in absolute ether was cooled to 0 °C. The resulting colorless suspension was stirred at this temperature for about 20 min. A mixture of the appropriate ketone with an excess of ethyl formate was then slowly added drop wise over a period of 90 min. After the complete addition the reaction mixture was allowed to warm to room temperature and stirred for another 18 h. After vacuum filtration the solids were rinsed twice with ether and dried in vacuum. The sodium salts obtained in this fashion were utilized without further purification in procedure B.

B: Preparation of the 3-cyano-2-pyridone derivatives (4, 5, 6, 7, 8) from α -hydroxymethylene-ketone sodium salts: To a solution of the respective sodium salts (see method A) in water an excess of cyanoacetamide and freshly prepared piperidinium acetate solution (composed of: 20% AcOH, 45% water and 35% piperidine) was added. The yellow to red colored solution was refluxed for 4 h and acetic acid was then added cautiously to the hot solution. The resulting suspension was allowed to cool to room temperature and stirred for another 12 h. The residue was filtered off, washed with ice water and dried in vacuum. Repeated recrystallization from acetic acid and subsequent column chromatography yields the analytically pure pyridones 4–8.

6-Methyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (2) [21]: To a solution of 4,4-dimethoxy-2-butanone (375 mmol, 50 ml) and cyanoacetamide (423 mmol, 35.6 g) in water (100 ml) a freshly prepared piperidinium acetate solution (60 ml of water, 15 ml of AcOH and an appropriate amount of piperidine until the pH value is 9.5) was added and then the suspension was refluxed for 24 h. During this period the reactants first went completely into solution until the product started precipitating out after approximately 3 h. After completion time the suspension was cooled to room

temperature, filtered and the residue washed well with ice water, until the filtrate appears nearly colorless. The crystals were recrystallized twice from $\text{H}_2\text{O}/\text{EtOH}$ (1:1) with little charcoal to obtain colorless needles (28.6 g, 57%), m.p. 286 °C (dec.). – ^1H NMR (300 MHz, $[\text{D}_6]\text{-DMSO}$): $\delta = 12.53$ (s, 1H, NH), 7.99 (d, $J = 7.4$ Hz, 1H, H-4), 6.19 (dd, $J = 7.4$ Hz, $J = 0.6$ Hz, 1H, 5-H), 2.26 (d, $J = 0.6$ Hz, 3H, CH_3). – ^{13}C NMR (75.5 MHz, $[\text{D}_6]\text{-DMSO}$): $\delta = 160.9$ (CO), 153.9 (C-4), 149.0 (C-5), 117.0 (CN), 105.2 (C- CH_3), 99.8 (C-CN), 19.5 (CH_3). – EI-MS (70 eV): m/z (%) = 134 (100) $[\text{M}^+]$, 119 (6) $[\text{M}^+ - \text{CH}_3]$, 116 (3), 107 (4) $[\text{M}^+ - \text{HCN}]$, 106 (39) $[\text{M}^+ - \text{CO}]$, 105 (87) $[\text{M}^+ - \text{CO}, -\text{H}]$, 91 (3), 79 (6), 78 (6), 64 (23), 63 (8), 62 (3). – UV/vis (MeOH): λ_{max} (lg ϵ) = 335.1 (0.43), 205.9 (0.41), 236.8 (0.26). – IR (KBr): $\nu = 3436$ cm^{-1} (br, m), 2991 (m), 2851 (m), 2224 (s), 1667 (ss), 1619 (s), 1563 (m), 1487 (m), 1326 (s), 1216 (m), 1167 (m), 933 (m), 832 (m), 770 (m). $\text{C}_7\text{H}_6\text{N}_2\text{O}$ (134.14): calcd. C 62.68, H 4.51, N 20.88; found C 62.52, H 4.58, N 20.95.

6-Ethyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (3): LDA was generated *in situ* by adding cautiously BuLi (32.5 mmol, 13 ml) to a stirred solution of diisopropylamine (32.8 mmol, 4.61 ml) in THF (150 ml) at 0 °C. After 15 min the solution was treated in portions with pyridone derivative 2 (14.9 mmol, 2.0 g) [22]. The solid immediately dissolved and the color of the solution changed to deep orange. The mixture was kept at 0 °C for 2 h before methyl iodide (14.5 mmol, 0.9 ml) in absolute THF (15 ml) was added dropwise. The resulting mixture was cooled for another 2 h, then allowed to warm up to room temperature and stirred for another 16 h. The solvent was evaporated under reduced pressure, the residue is taken up in water (150 ml) and extracted with ether (2×100 ml). The aqueous layer was acidified with 2 M HCl to pH 4.5–5 and stored for 1 d at 3–4 °C. The precipitate was filtered, washed with little 2-propanol and ether to give crude 3 (1.16 g, 56%). Flash column chromatography ($\text{CHCl}_3/\text{MeOH}$, 10:1, $R_f = 0.45$) gave pure 3 as a nearly colorless solid (349 mg, 16%), m.p. 244 °C (dec.). – ^1H NMR (300 MHz, $[\text{D}_6]\text{-DMSO}$): $\delta = 13.41$ (s, 1H, NH), 7.81 (d, $J = 7.5$ Hz, 1H, H-4), 6.21 (d, $J = 7.5$ Hz, 1H, H-5), 2.74 (q, $J = 7.5$ Hz, 2H, CH_2), 1.32 (t, $J = 7.5$ Hz, 3H, CH_3). – ^{13}C NMR (75.5 MHz, $[\text{D}_6]\text{-DMSO}$): $\delta = 163.3$ (CO), 158.6 (C-4), 148.6 (C-5), 115.7 (CN), 104.8 (C- CH_2), 101.3 (C-CN), 26.9 (CH_2), 12.4 (CH_3). – EI-MS (70 eV): m/z (%) = 148 (75) $[\text{M}^+]$, 147 (100) $[\text{M}^+ - \text{H}]$, 129 (5), 121 (5) $[\text{M}^+ - \text{HCN}]$, 120 (6) $[\text{M}^+ - \text{CO}]$, 119 (6) $[\text{M}^+ - \text{CO}, -\text{H}]$, 105 (9), 92 (8), 64 (9). – UV/vis (MeOH): λ_{max} (lg ϵ) = 205.9 (1.20), 335.0 (1.06), 236.1 (0.64). IR (KBr): $\nu = 3435$ cm^{-1} (br, m), 3153 (m), 3100 (m), 2986 (s), 2942 (m), 2867 (m), 2224 (s), 1649 (ss), 1604 (s), 1568 (s), 1493 (m), 1463 (m), 1314 (m), 1204 (m), 1166 (m), 813 (m). – $\text{C}_8\text{H}_8\text{N}_2\text{O}$ (148.16): calcd. C 64.85, H 5.44, N 18.91; found C 64.76, H 5.59, N 18.92.

6-Isopropyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (**4**): Following procedure **A**, 1-hydroxy-methylene-3-methyl-2-butanone sodium salt was generated by the treatment of isopropylmethylketone (32.2 mmol, 3.45 ml) and ethyl formate (50 mmol, 4.03 ml) in absolute ether (250 ml) and NaOMe (50 mmol, 2.70 g). The obtained slightly yellow sodium salt (2.61 g, 60%) was used without further purification in procedure **B**. A mixture of sodium salt (19.2 mmol, 2.61 g) and cyanoacetamide (21.2 mmol, 1.78 g) in water (40 ml) with 1.35 ml piperidinium acetate solution (preparation see procedure **B**) was refluxed. Acidification was performed by adding 2.1 ml of AcOH to the hot reaction mixture. The crude product was obtained as a yellow solid (1.63 g, 52%). Flash column chromatography of (CHCl₃/MeOH, 15:1, *R_f* = 0.46) gave pure **4** as nearly colorless fluffy needles (734 mg, 45%), m.p. 211 °C (dec.). ¹H NMR (400 MHz, CDCl₃): δ = 13.32 (s, 1H, NH), 7.81 (d, *J* = 7.6 Hz, 1H, 4-H), 6.20 (d, *J* = 7.6 Hz, 1H, 5-H), 2.97 (sept., *J* = 6.8 Hz, 1H, 7-H), 1.32 (d, *J* = 6.8 Hz, 6H, 2 × CH₃). – ¹³C NMR (100.57 MHz, CDCl₃): δ = 163.2 (CO), 162.8 (C-4), 148.7 (C-5), 115.7 (CN), 103.1 (C-CH), 101.4 (C-CN), 32.9 (CH), 21.3 (2 × CH₃). – EI-MS (70 eV): *m/z* (%) = 162 (36) [M⁺], 161 (17) [M⁺ - H], 148 (9) [M⁺ - CH₂], 147 (100) [M⁺ - H, - CH₂], 134 (7), 129 (6), 119 (9), 92 (7), 65 (5), 64 (11), 39 (5). – UV/vis (MeOH): λ_{max}(lg ε) = 205.0 (0.43), 335.0 (0.39), 235.0 (0.23). – IR (KBr): ν = 3435 cm⁻¹ (br, m), 3308 (m), 3260 (m), 3156 (m), 3086 (m), 2975 (s), 2225 (s), 1657 (ss), 1597 (s), 1568 (m), 1320 (m), 1200 (m), 1185 (m), 811 (m). – C₉H₁₀N₂O (162.19): calcd. C 66.65, H 6.21, N 17.27; found C 66.35, H 6.21, N 17.44.

6-tert-Butyl-2-oxo-1,2-dihydro-pyridine-3-carbonitrile (**5**): According to procedure **A** the 1-hydroxymethylene-3,3-dimethyl-2-butanone sodium salt was generated by treatment of 3,3-dimethyl-2-butanone (30 mmol, 3.74 ml) with ethyl formate (32 mmol, 2.58 ml) and NaOMe (32 mmol, 1.73 g) in absolute ether (250 ml). The brownish solid (2.57 g, 57%) was used without further purification in procedure **B**. A mixture of sodium salt (17.1 mmol, 2.57 g) and cyanoacetamide (18.6 mmol, 1.56 g) in water (40 ml) with 1.20 ml of a piperidinium acetate solution (preparation see procedure **B**) was refluxed. Acidification was performed by adding 1.87 ml of AcOH to the hot reaction mixture. The crude product was obtained as a dark yellow solid (1.33 g, 44%). Flash column chromatography of (hexane/EtOAc, 5:1, *R_f* = 0.20) gave pure **5** as nearly colorless crystals (1.12 g, 37%), m.p. 203–204 °C. – ¹H NMR (400 MHz, CDCl₃): δ = 12.73 (s, 1H, NH), 7.79 (d, *J* = 7.6 Hz, 1H, 4-H), 6.24 (d, *J* = 7.6 Hz, 1H, 5-H), 1.39 (s, 9H, 3 × CH₃). – ¹³C NMR (100.57 MHz, CDCl₃): δ = 164.4 (CO), 162.7 (C-4), 148.4 (C-5), 115.7 (CN), 102.2 (C-C_q), 101.9 (C-CN), 35.9 (C_q), 28.7 (3 × CH₃). – EI-MS (70 eV): *m/z* (%) = 176 (24) [M⁺], 175 (7) [M⁺ - H], 162 (10) [M⁺ - CH₂], 161 (100)

[M⁺ - H, - CH₂], 134 (8), 116 (6), 64 (7), 41 (6), 39 (5). – UV/vis (MeOH): λ_{max}(lg ε) = 205.2 (0.46), 334.3 (0.41), 233.9 (0.24). – IR (KBr): ν = 3424 cm⁻¹ (br, w), 3164 (m), 3065 (m), 2970 (s), 2908 (s), 2231 (s), 1649 (ss), 1590 (ss), 1567 (ss), 1492 (m), 1464 (m), 1328 (s), 1229 (m), 1212 (m), 1191 (m), 875 (m), 934 (m), 918 (w), 824 (m), 815 (m). – C₁₀H₁₂N₂O (176.22): calcd. C 68.16, H 6.86, N 15.90; found C 68.11, H 6.89, N 15.64.

2-Oxo-1,5,6,7-tetrahydro-2H-1-pyridine-3-carbonitrile (**6**) [24]: According to procedure **A** 2-hydroxymethylene-cyclopentanone sodium salt was generated by the treatment of cyclopentanone (113 mmol, 10 ml) and ethyl formate (115 mmol, 9.27 ml) with NaOMe (115.1 mmol, 6.22 g) in absolute ether (300 ml). The resulting light brown powder (15.1 g, 99%) was used without further purification in procedure **B**. A mixture of the sodium salt (96.4 mmol, 12.93 g) and cyanoacetamide (109 mmol, 9.18 g) in water (80 ml) with 8.6 ml of a piperidinium acetate solution (preparation see procedure **B**) was refluxed. Acidification was performed by adding 10.8 ml of AcOH to the hot reaction mixture. The crude product was recrystallized once from 80 ml of AcOH and little charcoal to obtain yellow needles (6.41 g, 42%). Flash column chromatography of 1.52 g (CHCl₃/MeOH, 20:1, *R_f* = 0.31) gave pure **6** as a slightly yellow solid (711 mg, 47%), m.p. 245 °C. – ¹H NMR (300 MHz, [D₆]-DMSO): δ = 12.71 (s, 1H, NH), 7.98 (s, 1H, 4-H), 2.79 (t, *J* = 7.5 Hz, 2H, 7-CH₂) 2.63 (t, *J* = 7.5 Hz, 2H, 5-CH₂) 2.02 (quin, *J* = 7.5 Hz, 2H, 6-CH₂). – ¹³C NMR (75.5 MHz, [D₆]-DMSO): δ = 161.1 (CO), 158.6 (C-9), 145.6 (C-4) 118.4 (C-8), 117.5 (CN), 99.2(C-CN), 31.5 (C-7), 28.8 (C-5), 22.6 (C-6). – EI-MS (70 eV): *m/z* (%) = 160 (87) [M⁺], 159 (100) [M⁺-H], 158 (2), 141 (3), 133 (2), 132 (10) [M⁺ - CO], 131 (14) [M⁺-H, -CO], 116 (4) [M⁺-CH₂NO], 106 (2) [M⁺ - CN, -CO], 105 (6) [M⁺-CN, -CO, -H], 104 (10) [M⁺ -CN, -CO, -2H], 89 (2), 78 (4), 77 (8), 76 (4), 65 (3), 64 (3), 63 (3), 53 (3), 52 (5), 51 (4), 50 (2), 43 (5), 41 (2), 39 (4). – UV/vis (MeOH): λ_{max}(lg ε) = 351.9 (0.42), 209.7 (0.28), 241.5 (0.25). – IR (KBr): ν = 3436 cm⁻¹ (br, m), 2945 (s), 2902 (s), 2848 (s), 2797 (s), 2767 (s), 2709 (s), 2225 (ss), 1650 (ss), 1605 (s), 1576 (m), 1541 (m), 1493 (s), 1464 (m), 1445 (m), 1391 (m), 1338 (s), 1299 (m), 1236 (s), 1146 (m), 954 (m), 771 (m). – C₉H₈N₂O (160.18): calcd. C 67.49, H 5.03, N 17.49; found C 67.32, H 5.01, N 17.49.

2-Oxo-1,2,5,6,7,8-hexahydro-3-quinoline-3-carbonitrile (**7**) [24]: Following procedure **A** 2-hydroxymethylene-cyclohexanone sodium salt was generated by treatment of cyclohexanone (77.4 mmol, 8 ml) and ethyl formate (81.9 mmol, 6.6 ml) with NaOMe (78.9 mmol, 4.26 g) in absolute ether (300 ml). The resulting light yellow powder (10.7 g, 93%) was used without further purification in procedure **B**. A mixture of the sodium salt (51.1 mmol, 7.56 g) and cyanoacetamide (56.4 mmol, 4.74 g) in 40 ml

water with 3.6 ml of a piperidinium acetate solution (preparation see procedure **B**) was refluxed. Acidification was performed by addition of AcOH (5.6 ml) to the hot reaction mixture. The crude product was recrystallized once from 40 ml of AcOH and little charcoal to obtain a nearly colorless solid (1.14 g, 28%). Flash column chromatography of 1.1 g (CHCl₃/MeOH, 15:1, *R_f* = 0.41) gave pure **7** as a colorless crystalline powder (806 mg, 73%), m.p. 255 °C. – ¹H NMR (300 MHz, [D₆]-DMSO): δ = 12.25 (s, 1H, NH), 7.86 (s, 1H, 4-H), 2.54 (t, *J* = 5.7 Hz, 2H, 8-CH₂), 2.40 (t, *J* = 5.5 Hz, 2H, 5-CH₂), 1.64 (m, 4H, 6-CH₂, 7-CH₂). – ¹³C NMR (75.5 MHz, DMSO-d₆): δ = 160.0 (CO), 151.0 (C-10), 150.1 (C-4), 116.9 (C-9), 113.3 (CN), 100.1 (C-CN), 26.8 (C-8), 25.2 (C-5), 21.7 (C-7), 20.8 (C-6). – EI-MS (70 eV): *m/z* (%) = 174 (100) [M⁺], 173 (30) [M⁺ - H], 159 (3), 147 (6) [M⁺ - H, -CN], 146 (80) [M⁺ - CO], 145 (5) [M⁺ - H, -CO], 128 (2), 118 (9.4), 104 (5), 91 (5), 77 (3), 64 (2), 41 (2), 52 (2), 39 (1). – UV/vis (MeOH): λ_{max}(lg ε) = 345.4 (0.52), 211.5 (0.52), 238.1 (0.33). – IR (KBr): ν = 3436 cm⁻¹ (br, m), 3147 (m), 2939 (s), 2864 (m), 2228 (s), 1658 (ss), 1609 (s), 1570 (s), 1487 (m), 1338 (m), 1164 (m), 948 (m), 812 (m), 768 (m). – C₁₀H₁₀N₂O (174.20): calcd. C 68.95, H 5.79, N 16.08; found C 68.86, H 5.74, N 16.06.

2-Oxo-1,5,6,7,8,9-hexahydro-2H-cyclohepta[b]pyridine-3-carbonitrile (8): According to procedure **A**, 2-hydroxymethylene-cycloheptanone sodium salt was generated by treatment of cycloheptanone (84.7 mmol, 10 ml) and ethyl formate (90.0 mmol, 7.25 ml) with NaOMe (87.0 mmol,

4.70 g) in absolute ether (300 ml). The resulting pale-yellow powder (13.6 g, 99%) was used without further purification in procedure **B**. A mixture of the sodium salt (79.1 mmol, 12.82 g) and cyanoacetamide (87.4 mmol, 7.35 g) in 80 ml of water with 5.6 ml of a piperidinium acetate solution (preparation see procedure **B**) was refluxed. Acidification was performed by addition of AcOH (9.0 ml) to the hot reaction mixture. The crude product was recrystallized once from 60 ml of AcOH and little charcoal to obtain a nearly colorless solid (4.45 g, 30%). Flash column chromatography of 1.00 g (CHCl₃/MeOH, 15:1, *R_f* = 0.29) gave pure **8** as a colorless solid (713 mg, 71%), m.p. 257–259 °C (dec.). – ¹H NMR (300 MHz, [D₆]-DMSO): δ = 12.44 (s, 1H, NH), 7.93 (s, 1H, 4-H), 2.73 (dt, *J* = 5.4 Hz, 2H, 9-CH₂), 2.54 (dt, *J* = 5.6 Hz, 2H, 5-CH₂), 1.75–1.69 (m, 2H, 7-CH₂), 1.58–1.53 (m, 2H, 8-CH₂), 1.50–1.44 (m, 2H, 6-CH₂). – ¹³C NMR (75.5 MHz, [D₆]-DMSO): δ = 160.3 (CO), 157.9 (C-11), 150.2 (C-4), 119.4 (C-10), 117.1 (CN), 98.2 (C-CN), 33.0 (C-9), 31.4 (C-5), 31.4 (C-7), 27.2 (C-6), 25.3 (C-8). – EI-MS (70 eV): *m/z* (%) = 188 (100) [M⁺], 187 (22) [M⁺ - H], 173 (16), 161 (3) [M⁺ - H, -CN], 160 (16) [M⁺ - CO], 159 (42) [M⁺ - H, -CO], 146 (27), 134 (14), 131 (7), 118 (5), 104 (7), 77 (5), 58 (5), 43 (15). – UV/vis (MeOH): λ_{max}(lg ε) = 347.0 (1.82), 209.3 (1.74), 241.7 (1.30). – IR (KBr): ν = 3436 cm⁻¹ (br, m), 2934 (ss), 2854 (s), 2794 (m), 2232 (s), 1649 (ss), 1599 (m), 1572 (s), 1484 (m), 1454 (m), 1347 (m), 1338 (m), 1194 (s), 964 (s), 772 (m). – C₁₁H₁₂N₂O (188.23): calcd. C 70.19, H 6.43, N 14.88; found C 70.19, H 6.39, N 14.90.

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- [19] The CCDC numbers contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033. Compound **2**: CCDC 241170; compound **3**: CCDC 241171; compound **4**: CCDC 241172; compound **5**: CCDC 241173; compound **6**: CCDC 241174; compound **7**: CCDC 241175; compound **8**: CCDC 241176.
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