The Problem of the Existence of C(Ar)–H ··· N Intramolecular Hydrogen Bonds in a Family of 9-Azaphenyl-9*H*-carbazoles

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In order to demonstrate the possibility of intramolecular hydrogen bonds (IMHB) between an aromatic C–H and a pyridine nitrogen atom, the family of 9-arylcarbazoles [Ar = phenyl (**1**), 2-pyridyl (**2**) or 2-pyrimidinyl (**3**)], their 9-aryl-1-azacarbazole analogues [Ar = phenyl (**4**), 2-pyridyl (**5**) or 2-pyrimidinyl (**6**)] and 9-phenyl-1,8-diazacarbazole (**7**), have been synthesized and the X-ray structure of all of them, except **4**, has been determined. The unit cell parameters are as follows. For **1**: a = 14.526(5) Å, b = 10.985(1) Å, c = 18.094(2) Å, β = 113.45(2)°, V = 2649(1) Å^3, Z = 8, $P2_1/n$. For **2**: a = 14.625(4) Å, b = 11.685(6) Å, c = 16.636(1) Å, β = 114.07(4)°, V = 2596(3) Å^3, Z = 8, $P2_1/n$. For **3**: a = 25.76(2) Å, b = 5.200(6) Å, c = 19.47(1) Å, β = 112.07(5)°, V = 2417(4) Å^3, Z =8, $C2/c$. For **5**: a = 12.825(2) Å, b = 12.336(4) Å, c = 16.468(6) Å, β = 111.41(3)°, V = 2426(2) Å^3, Z = 8, $P2_1/n$. For **6**: a = 10.682(3) Å, b = 29.033(9) Å, c = 7.524(3) Å, β = 90.46(3)°, V = 2333(1) Å^3, Z = 8, $P2_1/c$. For **7**: a = 10.895(2) Å, b = 13.407(4) Å, c = 17.552(6) Å, β = 107.81(2)°, V = 2441(2)Å^3, Z = 8, $P2_1/c$. The data were obtained at 293 K except for compound **7** for which the experimental temperature was 200 K. All compounds except **3** exist in the crystal in two different conformations. The potential curves corresponding to the rotation about the N(9)–C(aryl) bond of nine compounds (**1**–**7** plus the non-synthesized 2-pyridyl- and 2-pyrimidinyl-1,8-diaza analogues) have been calculated. The crystallographic torsion angles are near the zone of minimum energies according to AM1 calculations, save in the case of compound **1** (9-phenylcarbazole) where one of the independent molecules has a torsion angle of 78.4°, much larger than calculated. The calculated barrier through the planar state, ΔE^0, contains much information and appears to be related to the ^{1}H and ^{13}C chemical shifts of some selected molecules. Compound **3** [9-(2-pyrimidinyl)-9*H*-carbazole], with a torsion angle of 7.4(4)°, is the clearest representative of the existence of C–H ··· N IMHBs.

The aim of this paper was the study of the C–H ··· N hydrogen bond. Generally speaking, C–H ··· X (X = O, S, N) hydrogen bonds are important in: (i) determining crystal structures,[1–4] including organic superconducting molecules[5] and proteins;[6,7] (ii) drug–receptor binding;[8,9] and (iii) host–guest chemistry.[10–12] There is evidence, mainly from crystallography but also from *ab initio* calculations, that C–H ··· X (X = O, S, N) hydrogen bonds are: (i) always attractive;[5] (ii) much stronger and more directionally specific than it has been previously assumed;[2] and (iii) resemble O–H ··· X and N–H ··· X bonds far more than it was generally supposed.[13]

These conclusions always refer to intermolecular hydrogen bonds involving 'carbon acids'[14] which generally have large Taft's α values,[15] like alkynes[13,16] and malononitrile.[12] Intermolecular hydrogen bonds of less acidic compounds like alkenes,[13] heterocycles,[2,9,17–19] nitrobenzenes,[2] and benzene itself ('T-shaped geometry') have been also reported.[1,17,20,21] Due to our interest in IMHBs,[22] the present study was directed to C(Ar)–H ··· N IMHBs, where (Ar) stands for aromatic or heterocyclic rings.

These types of HBs could be present in compounds such as 2,2′-bipyridine (**I**)[23] or 1,1′-bipyrazole (**II**),[24] but the IMHBs form in these compounds five-membered pseudocycles which, according to AM1[PM3] calculations for a planar geometry, have not suitable H ··· N distances nor C–H ··· N angles: **I**, H ··· N = 2.42 [2.42] Å, C–H ··· N = 98.3 [98.3]°; **II**, H ··· N = 2.71 [2.84] Å, C–H ··· N = 90.3 [87.5]° (Fig. 1).

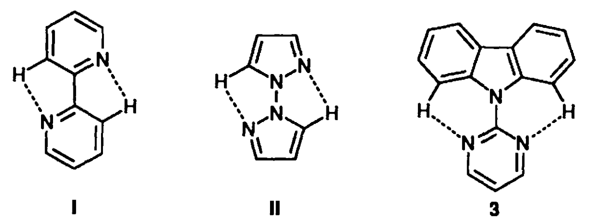

Fig. 1 IMHBs in 2,2′-bipyridine (**I**), 1,1′-bipyrazole (**II**) and 9-(2′-pyrimidinyl)carbazole (**3**)

On this basis, we designed nine structures derived from 9-phenylcarbazole (Fig. 2) in which the pseudocycles are six-membered rings and, consequently, have more favourable parameters for IMHBs. For instance, the calculated values for the planar structure of **3** (AM1 [PM3] calculations), give a shorter H ··· N distance (H ··· N = 2.31 [2.35] Å) and a more open C–H ··· N angle (C–H ··· N = 112.6 [113.4]°) than those of preceding examples.

The pseudocycles formed in compound **3** resemble those found in β-diketones **III** (Fig. 3), although they lack the so called 'resonance-assisted hydrogen bonding', which is important for stabilizing the chelate and thus rendering very strong IMHBs.[25,26] On the other hand, it has been stated[16] that the proton or hydrogen in a hydrogen bonding interaction is hard, in the Pearson sense,[27] because of its small size and lack of polarizability and, as a consequence, hard bases like aliphatic

Table 1 Selected structural data

Formula	Angles/° between least-squares planes 1–2[a]	C11–N1–C21–C(N)22 Dihedral angles/°	C11–N1–C21–C(N)26 Dihedral angles/°
$C_{18}H_{13}N$ (**1**)	78.40(9)	−107.9(4)	73.0(4)
b	54.8(1)	125.4(4)	−54.5(4)
$C_{17}H_{12}N_2$ (**2**)	61.9(2)	115.7(7)	−63.0(1)
b	47.6(2)	−131.8(7)	50.0(1)
$C_{16}H_{11}N_3$ (**3**)	6.97(8)	−172.2(3)	7.4(4)
$C_{16}H_{11}N_3$ (**5**)	36.8(4)	149.0(1)	−33.0(1)
b	33.6(2)	145.0(1)	−34.0(1)
$C_{15}H_{10}N_4$ (**6**)	37.1(3)	144.5(6)	−35.9(9)
b	33.6(3)	41.4(9)	−139.6(6)
$C_{16}H_{11}N_3$ (**7**)	55.0(3)	−120.0(1)	60.0(1)
b	40.4(3)	−133.0(1)	48.0(1)

[a] Plane 1: N1, C11, C(N)12, C13, C14, C15, C16, C31, C32, C33, C34, C35, C36. Plane 2: C21, C(N)22, C23, C24, C25, C(N)26. [b] Second molecule.

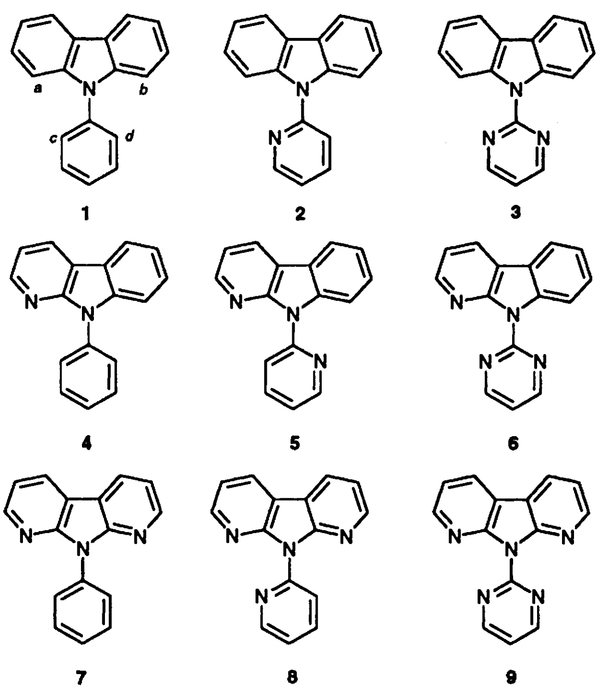

Fig. 2 Designed structures derived from **1** by replacement of the *a*–*d* C–Hs for nitrogen atoms

and heterocyclic amines should strongly interact with a C–H hydrogen bond donor.

Results and Discussion

Synthesis.—Compounds **1**–**6** were synthesized through Ullmann *N*-arylation reactions of 9*H*-carbazole and 9*H*-pyrido[2,3-*b*]indole using activated bronze copper as catalyst and potassium carbonate as base. Compounds **1** and **2** have been previously described,[28,29] but improved yields of **2** were obtained by sonication of the reaction mixture (see Experimental section). Compound **7** was synthesized through photochemical electrocyclization of phenylbis(2-pyridyl)amine, which was prepared by Ullmann *N*-arylation of bis(2-pyridyl)amine. A much improved yield of the last tertiary amine was achieved presonicating the copper powder (from 15%[28] to 91% yield).

Crystallography.—A summary of the crystallographic parameters for the investigated structures has been deposited at CCDC, and a selection of structural data in Table 1. The geometrical parameters of C–H ··· N intramolecular hydrogen bonds are given in Table 2. The crystallographic atom numbering is shown in Fig. 4.

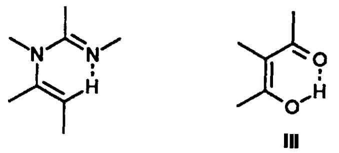

Fig. 3 IMHB in the designed structures and in β-diketones (**III**)

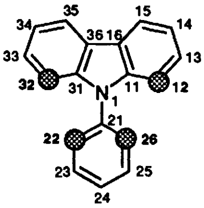

Fig. 4 Crystallographic atom numbering

The common feature in all the compounds studied is the presence of two independent molecules in the asymmetric unit, the only exception being compound **3**. These two conformers have similar relative orientations of the two main planes on each structure as can be seen in Table 1 and Figs. 5–6 and 8–10. By monitoring the value of the angle between the two main least-squares planes, or the torsion angle, a general tendency to planarity when C–H ··· N intramolecular contacts are possible can be observed. This tendency is particularly clear for compound **3**. No unusual features, neither geometrical (normal angles and distances) nor packing, were observed.

Tables 1 and 2 and Figs. 5–10 clearly establish the presence of intramolecular C–H ··· N interactions in compounds **3** and **5**. In the case of compound **3**, the experimental geometry [average values: torsion angle = 7.4(4)°, H ··· N distance = 2.31(2) Å, C–H ··· N angle = 114(2)°] compares well to that predicted from AM1 calculations (planar, H ··· N = 2.31 Å, C–H ··· N = 113°, see Introduction). This molecule shows two C–H ··· N contacts, C(32)–H(32) ··· N(22) and C(12)–H(12) ··· N(26). Molecule **5** also shows two such contacts, C(32)–H(32) ··· N(22) and C(26)–H(26) ··· N(12), with a very similar geometry in one of the two conformers, while in the other the geometry is less favourable. However, the C ··· N distances are similar, and only slightly longer than those observed for compound **3**. Similar contacts, but still longer and with a worse geometry, are observed in compound **6**. There is a linear relationship between the C ··· N distance (averaged values for compounds **3**, **5** and **6**) and the square of the torsion angle (10 values): $C \cdots N(\text{Å}) = 2.197 + 1.796 \times 10^{-4}\ (\text{torsion}°)^2$ $R = 0.81$.

Table 2 C–H Bond lengths, C···N and H···N distances (Å) and CH···N angles (°) of the interacting C(N)12 → N(C)26 and C(N)32 → N(C)22

	C(N)12 → N(C)26				C(N)32 → N(C)22			
Formula	C–H	C···N	H···N	C–H···N	C–H	C···N	H···N	C–H···N
$C_{17}H_{12}N_2$ (**2**)	—	—	—	—	0.95(5)	3.25(1)	2.82(5)	109.0(4)
a	—	—	—	—	1.06(7)	3.068(8)	2.58(5)	109.0(4)
$C_{16}H_{11}N_3$ (**3**)	0.96(3)	2.846(4)	2.30(2)	116.0(2)	0.99(3)	2.860(4)	2.32(2)	113.0(2)
$C_{16}H_{11}N_3$ (**5**)	1.1(1)	2.90(1)	2.1(1)	126.0(9)	1.1(1)	2.96(1)	2.2(1)	126.0(9)
a	1.2(1)	2.85(2)	2.3(1)	107.0(7)	1.0(1)	2.93(2)	2.4(1)	117.0(9)
$C_{15}H_{10}N_4$ (**6**)	—	—	—	—	1.07(7)	2.990(9)	2.36(7)	116.0(5)
a	—	—	—	—	1.08(1)	3.020(9)	2.487(9)	109.2(6)
$C_{16}H_{11}N_3$ (**7**)	1.08(2)	3.13(1)	2.87(1)	93.8(8)	1.0(1)	3.11(1)	2.81(9)	99.0(6)
a	1.08(2)	3.06(2)	2.68(1)	100.0(8)	1.12(8)	3.12(1)	2.8(1)	98.0(5)

[a] Second molecule.

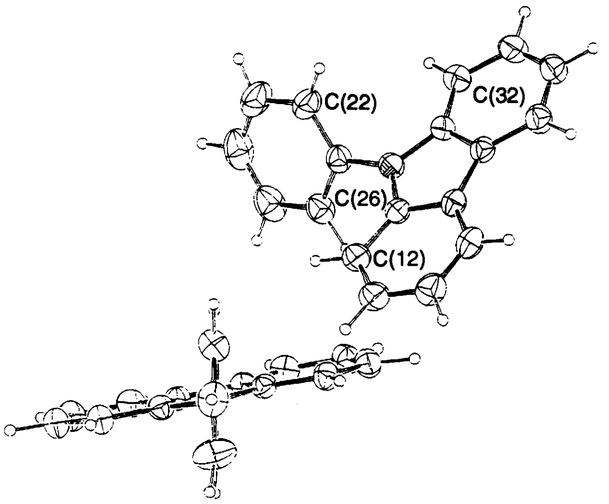

Fig. 5 Euclid[30] diagram of compound **1**

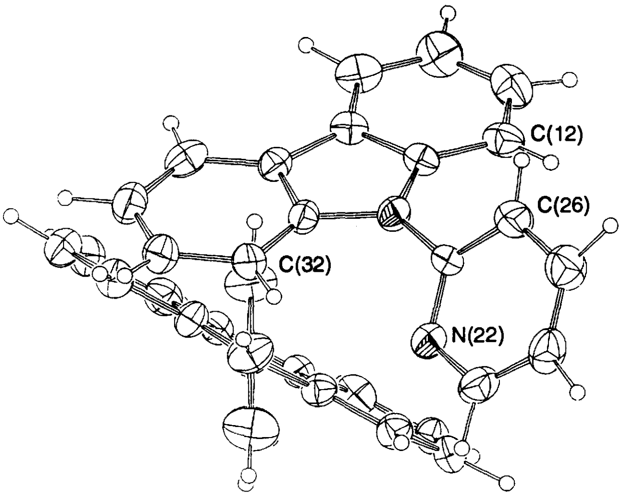

Fig. 6 Euclid[30] diagram of compound **2**

Regarding intermolecular contacts, compound **7** exhibits a weak interaction involving C(35) ··· N(32′) atoms [3.47(2) Å]. In compound **5**, the molecules are connected by a symmetry contact involving C(13) ··· N(12′) and C(13′) ··· N(12) atoms [3.49(2) Å]. No intermolecular contacts were observed in compound **3**, while both conformers in compound **6** show several weak contacts involving nitrogen atoms N(12) and N(12′).

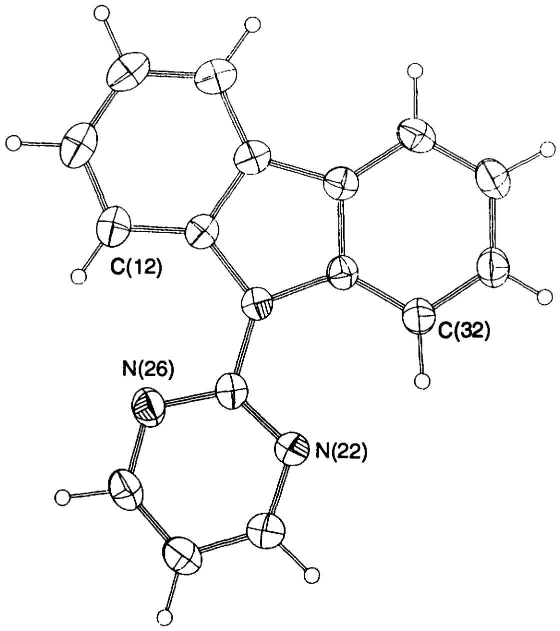

Fig. 7 Euclid[30] diagram of compound **3**

Semiempirical Calculations.—To achieve a better understanding of these findings and the relationship between the structure and the torsion angle, we decided to carry out theoretical calculations. Two barriers are found in the structures in Fig. 2, like in biphenyl derivatives: the 0° barrier, which is of steric origin and the 90° barrier, which is of electronic origin. The first one should diminish when there is an IMHB between a C–H and an N lone pair and it can be related to the steric requirements of the lone pair. The second one provides the driving force for the molecule to adopt a planar conformation and it is due to delocalization of the lone pair of carbazole N-9 atom into the ring of the 9-aryl substituent.

From a qualitative point of view, it might be expected that replacement of a C–H by a nitrogen atom in the carbazole ring (position *a* or *b* in Fig. 2, or positions 12 or 32 in crystallography) should either not affect the 90° barrier or lower it, because the electron-withdrawing effect of these nitrogen atoms would limit the availability of the N-9 lone pair for delocalization into the 9-aryl ring (see the polarized canonical form of **4** in Fig. 11).

On the contrary, a nitrogen atom in the 9-phenyl ring (position *c* or *d* in Fig. 2 or position 22 or 26 in crystallography) should increase the 90° barrier owing to the larger double bond character between N-9 and C-1′ [N(1)–C(21)] in crystallography. In fact, compounds **2** and **3** resemble 2-dimethylaminopyridine and 2-dimethylaminopyrimidine, which show high rotational barriers about the N–C(Ar) bond due to conjugation.[31,32]

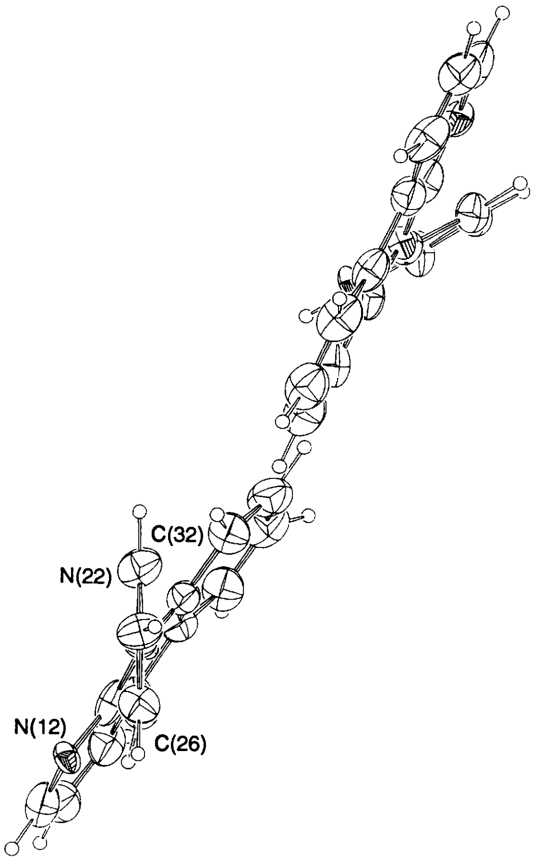

Fig. 8 Euclid[30] diagram of compound 5

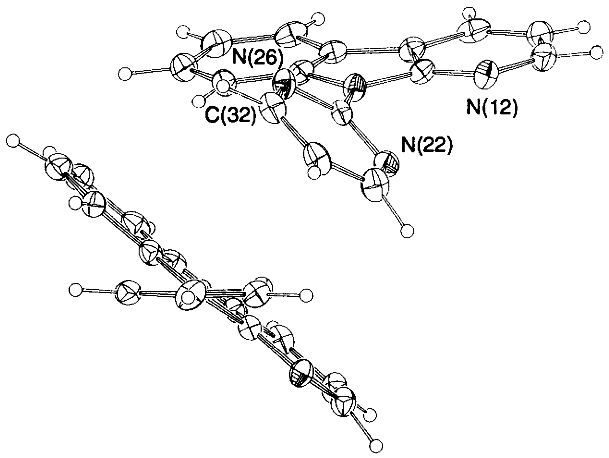

Fig. 9 Euclid[30] diagram of compound 6

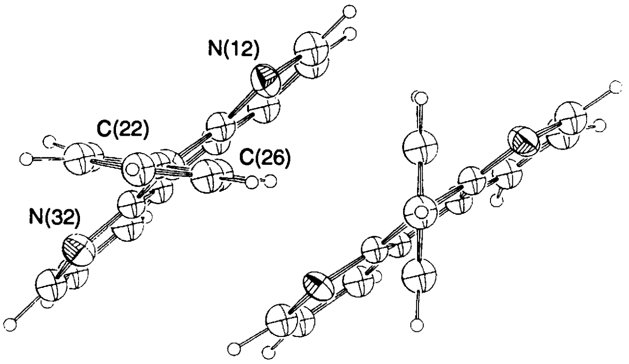

Fig. 10 Euclid[30] diagram of compound 7

The results of these AM1 calculations are represented in Fig. 12, where the heats of formation (in kcal $\mathrm{mol^{-1}}$) are plotted against the torsion angles. The experimental dihedral angles for those compounds whose geometry has been determined, **1–3** and **5–7** have been represented as black dots. To calculate the rotational barriers for compounds **1–9** we selected the semi-empirical AM1 method because it gives excellent results on this kind of problem. For instance, the twist angle of biphenyl is 44.4° (experimental value from electron diffraction), the calculated values being 46.26°, following HF/6-31G** calculations,[33] and 47.87°, following AM1 calculations (this work). For the sake of homogeneity, all compounds have been represented in the 0–180° range, even if only compound **5** lacks the 90° symmetry operation.

The calculated potential barriers at $\varphi = 90°$ (ΔE^{90}) and $\varphi = 0°$ (ΔE^{0}) are reported in Table 3.

It can be observed that the experimental dihedral angles are close to the minimum, the main exception being compound **1** where one of the conformers ($\varphi = 78.4°$) is much more twisted than the AM1 minimum (about 45°). This is particularly surprising since the most frequent observation is that the X-ray structure is more planar than the calculated one. For instance, the above mentioned calculated dihedral angle (φ) for biphenyl is 46.3°, but biphenyl is planar in the crystal ($\varphi = 0°$).[34]

The rotational barrier around the perpendicular conformation (ΔE^{90} in Table 3) can be analysed by comparing pairs of values. Introduction of a nitrogen atom in the carbazole ring either does not affect the barrier (**1** and **4**, **4** and **7** and **2** and **5**) or lowers it about 1.2 kcal $\mathrm{mol^{-1}}$ (**5** and **8**, **3** and **6** and **6** and **9**). A nitrogen atom in the phenyl ring either increases the barrier (**1** and **2**, **2** and **3** and **4** and **5**) or does not affect it (**5** and **6**, **7** and **8** and **8** and **9**). When nitrogen atoms are present in both rings (aryl and carbazole) their effects cancel. All these observations agree with the naive model depicted in resonance forms of Fig. 11.

The rotational barrier through the planar conformation is more relevant for this paper. The ten values of ΔE^{0} of Table 3 can be analysed by means of an additive model, considering four kinds of interactions *ac* and/or *bd* (Fig. 2): CH(carbazole)/CH(aryl), CH(carbazole)/N(aryl), CH(aryl)/N(azacarbazole) and N(azacarbazole)/N(aryl). The model is highly satisfactory ($r^2 = 0.999$, $S_d = 0.13$ kcal $\mathrm{mol^{-1}}$) and yields the following effects: CH(carbazole)/CH(aryl) = 5.36 kcal $\mathrm{mol^{-1}}$; CH(carbazole)/N(aryl) = 0.07 kcal $\mathrm{mol^{-1}}$; CH(aryl)/N(azacarbazole) = 1.92 kcal $\mathrm{mol^{-1}}$ and N(azacarbazole)/N(aryl) = 1.01 kcal $\mathrm{mol^{-1}}$.

The small value of the N/N interaction is related to the steric requirements of the nitrogen lone pair, considerably smaller than that of an aromatic C–H.[35] Since it includes the electronic repulsion of adjacent lone pairs,[36] the actual steric requirement should be even smaller. For the present study, the most significant effects are those of CH(aryl)/N(azacarbazole), which are larger than the N/N effects, and those of CH(carbazole)/N(aryl), which are much smaller (in fact they are not significantly different from 0).

According to Desiraju,[13] in the case of C–H ••• O bonds, the values of the distance between the carbon and the oxygen atoms are more sensitive to the nature of the H atom than to the nature of the oxygen atom: the more acidic the hydrogen, the shorter the bond. Thus, to account for the above reported values of CH/N terms, the carbazole CHs should be more acidic than the benzene CHs. In other words, polarized resonance forms of compounds **2** and **3** should contribute to their structure more than polarized resonance forms of compound **4** or **7** (Fig. 11).

A literature search about the acidity of the CHs of 9-phenylcarbazole (**1**) revealed that there is only a paper[37] reporting the lithiation of this compound. Against our expectations, the CHs

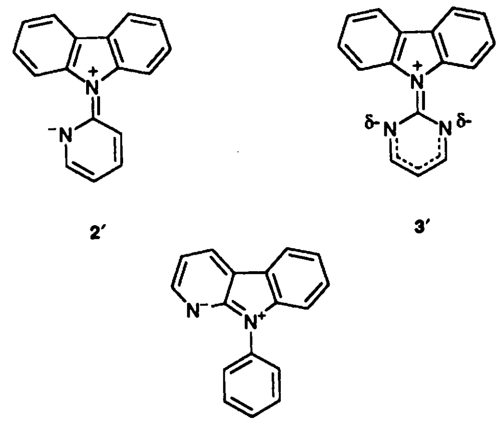

Fig. 11 Polarized canonical forms for compounds 2, 3 and 4

which are lithiated are those of positions 2′ and 6′ in the phenyl ring and not those of positions 1 and 8 in the carbazole ring. These facts were recently analysed in a review,[38] and led the authors to the conclusion that this unexpected result 'is probably because steric hindrance will force the phenyl ring orthogonal to the plane of carbazole, so that there will be little conjugative electron release from nitrogen to the phenyl ring to outweigh the (conformation-independent) $-$I effect of nitrogen; by contrast electrons may still be released conjugatively to the 1- and 8-positions of the carbazole ring'. But when a planar conformation is discussed, the expected greater acidity of carbazole CHs has to be observed.

NMR Spectroscopy.—Both ^{1}H and ^{13}C chemical shifts in biphenyl type derivatives are related to the twist angle. In the case of *N*-phenylazoles, the deshielding effect of a near nitrogen lone pair on the C–H proton chemical shift of the opposed ring and the sensitivity of phenyl *ortho* protons to the conformation of the molecule have been described.[39,40] Begtrup[41] showed that the difference $\Delta\delta = \delta_{meta} - \delta_{ortho}$ in ^{13}C NMR spectroscopy, can be used for assessing the extent of inter-annular conjugation. The method was extended by Fong to include substituent effects[42] and, finally, this approach was used to discuss the whole class of *N*-phenylazoles, including 9-phenylcarbazole **1**.[43]

Tables 4 and 5 show the ^{1}H and ^{13}C NMR data, respectively. For comparative purposes, we have used in NMR tables the atom numbering shown in Fig. 13. The assignment of signals was based on an intensive use of two dimensional experiments. The ^{1}H NMR experimental data of Table 4 have to be corrected for the effect of the nitrogen atom in the same ring. To this purpose, the ^{1}H NMR spectra of equimolar mixtures of benzene–pyridine and carbazole–α-carboline were recorded at 500 MHz using 5 mg of the mixture dissolved in 1 cm^3 of CDCl$_3$. This internal comparison showed that the pyridine β proton (δ = 7.25) is shifted upfield by 0.08 ppm with respect to benzene (δ = 7.33), whereas carboline 8-H proton (δ = 7.45) is shifted 0.11 ppm downfield with regard to carbazole 1-H and 8-H protons (δ = 7.34). The corrected chemical shifts for 8-H in **4** and 6-H in **5** are reported in italics in Table 6. The differences with the chemical shifts of phenylcarbazole (**1**), are noted $\Delta\delta$(Carb) and $\Delta\delta$(Ph). The $\Delta\delta^{13}$C values corresponding to $\delta_{meta} - \delta_{ortho}$ of the three phenyl derivatives **1**, **4** and **7** were calculated from Table 5 values.

Accepting the hypothesis that the barrier going through the planar form (ΔE^0) is related to these NMR $\Delta\delta$ values and that this relationship is a quadratic one, as is usual with this kind of potentials,[45] the following equations are found:

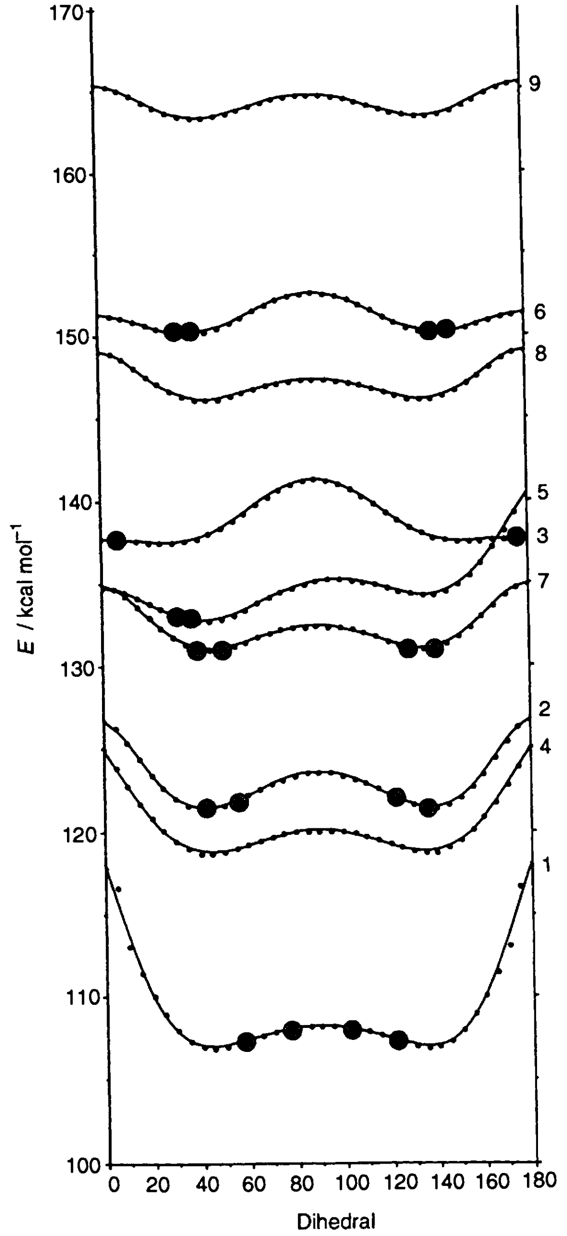

Fig. 12 Potential curves corresponding to the rotation about the N(9)–C(aryl) bond calculated for structures **1**–**9**

$$\sqrt{\Delta E^0} = 3.20 - 1.836\,\Delta\delta(\text{Carb}), n = 6, r^2 = 0.992 \quad (1)$$

$$\sqrt{\Delta E^0} = 3.23 - 3.919\,\Delta\delta(\text{Ph}), n = 5, r^2 = 0.991 \quad (2)$$

$$\sqrt{\Delta E^0} = -0.686 - 1.470\,\Delta\delta^{13}\text{C}, n = 3, r^2 = 0.998 \quad (3)$$

The main significance of these relationships is that they represent a bridge between the gas phase (AM1 calculations) and the solution (NMR spectroscopy). It should be noted that for compound **5** only the 2.0 kcal mol^{-1} barrier is consistent with the NMR results.

Conclusions

X-Ray crystallography as well as semiempirical calculations and NMR studies in solution point to 2′-pyrimidylcarbazole (**3**) as a clear representative of a compound with C–H···N IMHB. The design of these molecules as models for such hydrogen bonds has been rewarding, although the difference between the two reciprocal situations illustrated by compounds

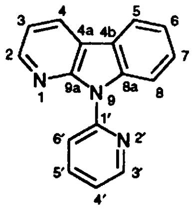

Fig. 13 NMR atom numbering

3 and 7 came as a surprise. The pyridine lone pair is not only smaller than an aromatic CH,[35] but in some cases it is distinctly attractive towards one of such CHs. This conclusion has to be included in any design of supramolecular structure and in discussions of natural assemblies.

Table 3 Calculated potential barriers (in kcal mol^{-1}) to the N–C(aryl) rotation in structures **1–9**

Structure	ΔE^{90}	ΔE^{0}
1	1.3	10.9
2	2.2	5.3
3	3.8	0.2
4	1.3	7.1
5a[a]	2.4	2.0
5b[a]	2.4	6.3
6	2.4	1.1
7	1.4	3.9
8	1.2	3.0
9	1.3	2.0

[a] Correspond to the two planar conformations of compound **5** (see text); obviously, they are identical in the perpendicular conformation.

Experimental

Chemistry.—Melting points were measured on a Reichert microscope apparatus and are uncorrected. ^{1}H and ^{13}C NMR spectra were obtained in $CDCl_3$ with Me_4Si as an internal standard and were recorded on a Varian VXR-300S (^{1}H at 300 MHz, ^{13}C at 75.4 MHz) or Bruker AC-200P (^{1}H at 200 MHz) spectrometers. UV irradiation was carried out with a high pressure mercury lamp (Hanau TQ-150) provided with a Pyrex filter. Sonication was performed with a Virsonic 300 cell disrupter operating at 20 KHz.

All solvents and chemicals were of reagent grade quality, commercially purchased and used without further purification except as noted below. Cyclohexane for use in photocyclisation reactions was distilled from sodium and stored over sodium wire. Dimethylformamide (DMF) was distilled under reduced pressure and stored over 4 Å molecular sieves. Activation of copper was carried out by a standard procedure.[46] 9*H*-Pyrido[2,3-*b*]indole was prepared following ref. 47. All reactions were monitored by thin layer chromatography (TLC) on aluminium plates coated with alumina and a fluorescent indicator (Scharlau cf. 300). Separations by flash chromatography were performed on alumina columns.

*9-Phenyl-*9H*-carbazole* (**1**).—A mixture of 9*H*-carbazole (1 g, 6 mmol), K_2CO_3 (1 g, 7 mmol), activated copper bronze (0.1 g, 1.5 mmol) and iodobenzene (10 cm^3, 88 mmol) was stirred and heated at reflux at 200 °C for 5 h. The reaction mixture was extracted with 25 cm^3 portions of hot acetone until the extracts were pale in colour. The acetone extracts were concentrated on a rotary evaporator and then iodobenzene was removed by vacuum distillation. The crude product was purified by chromatography on alumina with light petroleum (b.p. 40–60 °C)–benzene (8:1) as eluent to give pure product (0.75 g,

Table 5 ^{13}C Chemical shifts (δ in ppm) in $CDCl_3$

Compd.	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-4a
1[a]	109.7	125.9	119.9	120.3	120.3	119.9	125.9	109.7	123.3
2	111.0	126.1	120.1	120.8	120.8	120.1	126.1	111.0	121.1
3	116.3	126.5	119.4	122.2	122.2	111.4	126.5	116.3	125.7
4	—	146.4	116.0	128.2	120.8	120.6	126.8	110.3	116.3
5	—	145.9	116.8	128.2	120.2	121.6	127.3	113.3	117.3
6	—	146.8	117.7*	128.2	122.4	120.4	120.4	114.0	118.1
7	—	147.4	116.9	129.0	129.0	116.9	147.4	—	114.3

Compd.	C-4b	C-8a	C-9a	C-1′	C-2′	C-3′	C-4′	C-5′	C-6′
1[a]	123.3	140.8	140.8	137.6	127.1	129.8	127.4	129.8	127.1
2	121.1	139.5	139.5	152.0	—	149.5	124.2*	136.4	119.0*
3	125.7	139.1	139.1	159.0	—	157.7	115.8	157.7	—
4	120.7	140.0	157.1	136.2	127.3	129.6	127.5	129.6	127.3
5	121.2	138.9	151.1**	150.8**	—	148.6	121.4*	138.0	120.5*
6	122.0	138.4	151.3	157.4	—	158.6	117.9	158.6	—
7	114.3	151.4	151.4	134.9	127.5	129.3	127.7	129.3	127.5

[a] Consistent with literature data in DMSO.[44] *,** These assignments can be reversed.

Table 6 NMR parameters and torsional barriers for compounds **1–7**

Compd.	1-H	8-H	2′-H	6′-H	Δδ(Carb)	Δδ(Ph)	$\Delta\delta^{13}$C	ΔE^{0}
1	7.34	7.34	7.49	7.49	0	0	−2.7	10.9
2	7.85	7.85	—	*7.73*	0.51	0.24	—	5.3
3	8.87	8.87	—	—	1.53	—	—	0.2
4	—	*7.56*	7.62	7.62	0.22	0.13	−2.3	7.1
5	—	*8.34*	—	*7.97*	1.00	0.48	—	2.0[a]
6	—	*8.45*	—	—	1.11	—	—	1.1
7	—	—	7.79	7.79	—	0.30	−1.8	3.9

[a] The lowest barrier.

Table 4 ^1H NMR spectroscopic data (δ in ppm, coupling constants in Hz) in $CDCl_3$

Compd.	1-H	2-H	3-H	4-H	5-H	6-H	7-H	8-H	2′-H	3′-H	4′-H	5′-H	6′-H
1	7.34(m)	7.34(m)	7.23(m)	8.09(ddd) *J* 7.9, 1.2, 0.8	8.09(ddd)	7.23(m)	7.34(m)	7.34(m)	7.49(m)	7.49(m)	7.34(m)	7.49(m)	7.49(m)
2	7.85(d) *J* 8.2	7.46(m)	7.33(m)	8.13(d) *J* 7.2	8.13(d)	7.33(m)	7.46(m)	7.85(d) *J* 8.2	—	8.72(dd) *J* 4.9, 1.9	7.28(m)	7.62(d) *J* 8.0	7.81(td) *J* 8.0, 1.9
3	8.87(d) *J* 8.3	7.53(td) *J* 8.3, 7.2, 1.3	7.39(t) *J* 7.2	8.09(d) *J* 7.3	8.09(d)	7.39(t) *J* 7.2	7.53(td) *J* 8.3, 7.2, 1.3	8.87(d) *J* 8.3	—	8.79(d) *J* 4.8	7.05(t) *J* 4.8	8.79(d) *J* 4.8	—
4	—	8.48(dd) *J* 4.8, 1.6	7.21(dd) *J* 7.7, 4.8	8.36(dd) *J* 7.7, 1.6	8.11(dd) *J* 7.8, 0.7	7.32(ddd) *J* 7.8, 6.0, 2.0	7.45(m)	7.45(m)	7.62(m)	7.58(m)	7.45(m)	7.58(m)	7.62(m)
5	—	8.48(dd) *J* 4.9, 1.6	7.23(dd) *J* 7.7, 4.9	8.32(dd) *J* 7.7, 1.6	8.17(dt) *J* 8.2	7.34(ddd) *J* 8.2, 7.2, 0.9	7.54(ddd) *J* 8.4, 7.2, 0.9	8.3(dt) *J* 8.4	—	8.66(ddd) *J* 4.9, 1.9, 0.8	7.25(ddd) *J* 7.4, 4.9, 1.3	7.92(ddd) *J* 8.0, 7.4, 1.9	8.05(ddd) *J* 8.0, 1.3, 0.8
6	—	8.63(d) *J* 5.1	7.28(dd) *J* 7.6, 5.1	8.34(d) *J* 7.6	8.03(d) *J* 7.5	7.36(t) *J* 7.5	7.51(t) *J* 7.6	8.34(d) *J* 7.6	—	8.95(d) *J* 4.8	7.22(t) *J* 4.8	8.95(d) *J* 4.8	—
7	—	8.56(dd) *J* 4.9, 1.7	7.30(dd) *J* 7.8, 4.9	8.38(dd) *J* 7.8, 1.7	8.38(dd)	7.30(dd) *J* 7.8, 4.9	8.56(dd) *J* 4.9, 1.7	—	7.79(dd) *J* 7.8, 1.3	7.62(t) *J* 7.8	7.47(tt) *J* 7.8, 1.3	7.62(t) *J* 7.8	7.79(dd) *J* 7.8, 1.3

52%); m.p. 92 °C (lit.,[28] 91 °C) (Found: C, 88.9; H, 5.35; N, 6.1. Calc. for $C_{18}H_{13}N$: C, 88.86; H, 5.39; N, 5.76%).

9-(2-*Pyridyl*)-9H-*carbazole* (**2**).—A mixture of 9*H*-carbazole (0.9 g, 5.4 mmol), K_2CO_3 (0.9 g, 6.5 mmol), copper bronze (0.1 g, 1.5 mmol) and 2-bromopyridine (9 cm^3, 93 mmol) was refluxed at 200 °C and treated with ultrasonic irradiation for 5 h. The reaction mixture was extracted with hot acetone and then concentrated on a rotary evaporator; 2-bromopyridine (5.5 cm^3, 61%) was recovered by vacuum distillation. The resulting brown oil thus obtained (1.3 g) was purified by chromatography on alumina with benzene as the eluent to give **2** (0.92 g, 70%) as a pale oil which solidified at room temperature; m.p. 90–92 °C (lit.,[29] 92–93 °C) (Found: C, 84.2; H, 5.0; N, 11.9. Calc. for $C_{17}H_{11}N_2$: C, 83.93; H, 4.56; N, 11.51%).

9-(2-*Pyrimidinyl*)-9H-*carbazole* (**3**).—Carbazole (0.8 g, 4.8 mmol), K_2CO_3 (0.8 g, 5.8 mmol), 2-chloropyrimidine (0.6 g, 5.2 mmol), activated copper bronze (0.1 g, 1.5 mmol) and dry DMF (9 cm^3) were stirred and refluxed at 180 °C for 5 h. The cold reaction mixture was then poured onto water (50 cm^3) and the resulting precipitate was filtered to give **3** (0.7 g, 60%) as white-yellow needles; m.p. 105–108 °C (from light petroleum) (Found: C, 78.25; H, 4.6; N, 17.1. Calc. for $C_{16}H_{11}N_3$: C, 78.35; H, 4.52; N, 17.13%).

9-*Phenyl*-9H-*pyrido*[2,3-b]*indole* (**4**).—A mixture of 9*H*-pyrido[2,3-*b*]indole (0.2 g, 1.2 mmol), K_2CO_3 (0.2 g, 1.4 mmol), activated copper bronze (0.02 g, 0.3 mmol) and iodobenzene (2 cm^3, 17 mmol) was stirred and refluxed at 200 °C for 5 h. The reaction mixture was extracted with hot ethanol until the extracts were pale in colour. The ethanol extracts were concentrated on a rotary evaporator and iodobenzene was removed by vacuum distillation. The crude product was purified by chromatography on alumina with light petroleum–CH_2Cl_2 (7:5) as the eluent to give the pure product (0.17 g, 59%) as a white-pink powder; m.p. 109–111 °C (Found: C, 83.4; H, 4.95; N, 11.45. Calc. for $C_{17}H_{12}N_2$: C, 83.58; H, 4.95; N, 11.47%).

9-(2-*Pyridyl*)-9H-*pyrido*[2,3-b]*indole* (**5**).—9*H*-Pyrido[2,3-*b*]indole (0.2 g, 1.2 mmol), K_2CO_3 (0.2 g, 1.4 mmol) activated copper bronze (0.02 g, 0.3 mmol) and 2-bromopyridine (2 cm^3, 20 mmol) were stirred and refluxed at 205 °C for 2 h, until 9*H*-pyrido[2,3-*b*]indole disappeared. The reaction mixture was extracted with hot acetone and the extract was concentrated on a rotary evaporator. The crude product was purified by chromatography on alumina with CH_2Cl_2–light petroleum (7:4) as eluent or by crystallization to give **5** (0.27 g, 93%) as light yellow crystals; m.p. 87–89 °C (from hexane) (Found: C, 78.5; H, 4.6; N, 17.0. Calc. for $C_{16}H_{11}N_3$: C, 78.35; H, 4.52; N, 17.13%).

9-(2-*Pyrimidinyl*)-9H-*pyrido*[2,3-b]*indole* (**6**).—9*H*-Pyrido-[2,3-*b*]indole (0.22 g, 1.3 mmol), K_2CO_3 (0.22 g, 1.6 mmol), 2-chloropyrimidine (0.2 g, 1.7 mmol), activated copper bronze (0.02 g, 0.3 mmol) and dry DMF (9 cm^3) were stirred and refluxed at 186 °C for 5 h. The solvent was removed by distillation and the crude mixture was purified by chromatography on alumina with CH_2Cl_2–benzene (2:1) as eluent to give **6** (0.2 g, 62%) as a yellow powder; m.p. 156–158 °C (Found: C, 73.3; H, 4.2; N, 22.6. Calc. for $C_{15}H_{16}N_4$: C, 73.16; H, 4.09; N, 22.75%).

9-*Phenyl*-9H-*dipyrido*[2,3-b:3′,2′-d]*pyrrole* (**7**).—To a mixture of bis(2-pyridyl amine (0.8 g, 4.7 mmol), K_2CO_3 (0.8 g, 5.8 mmol) and copper powder (0.03 g, 0.5 mmol), after 35 min of sonication, was added iodobenzene (2 cm^3), and then refluxed for 5 h. The reaction mixture was extracted with hot acetone and after evaporation of the solvent the residue was purified by chromatography on alumina with CH_2Cl_2–EtOAc (15:1). The pale oil thus obtained was dissolved in CH_2Cl_2 and filtered through dry alumina to give phenylbis(2-pyridyl)amine (1.06 g, 91%); m.p. 90–92 °C (lit.,[48] 94 °C); δ_H 6.90 (2 H, t, pyridyl 5-H), 6.98 (2 H, d, *J* 8.5, phenyl 2′-H and 6′-H), 7.12 (3 H, m, 3′-H and 5′-H), 7.35 (2 H, t, 3-H), 7.53 (2 H, t, *J* 7.7, 4-H), 8.22 (2 H, d, *J* 4.2, 6-H).

A stirred solution of phenylbis(2-pyridyl)amine (139 mg, 0.56 mmol) in cyclohexane (400 cm^3) was irradiated for 30 h under N_2. After evaporation of the solvent, the residue was purified by chromatography on alumina with benzene as eluent to give **7** (11 mg, 8%); m.p. 144–146 °C (Found: C, 78.29; H, 4.85; N, 17.05. Calc. for $C_{16}H_{11}N_3$: C, 78.35; H, 4.52; N, 17.13%).

Crystal Growth of Compounds **1–3** *and* **5–7**.—Crystals were grown at room temperature from light petroleum/benzene (**1**), xylene (**3** and **7**), hexane (**5**), butanol (**6**). Crystals of **2** were obtained at room temperature by vapour diffusion of light petroleum into a dichloromethane solution.

X-Ray Structure Determination.—Data collection of all compounds was performed on a Enraf–Nonius CAD4 single crystal diffractometer equipped with Mo-Kα radiation (λ = 0.710 73 Å). The data were collected at 293 K except for compound **7** (T = 200 K). Unit cell dimensions were determined from the angular settings of 25 reflections. The reflections measured, *hkl* range and θ limits were collected and have been deposited.* ω-2 θ scan technique with a variable scan rate and a maximum scan time of 60 s per reflection. Intensity was checked throughout data collection by monitoring three standard reflections every 60 min. Final drift corrections have been deposited.* On all reflections profile analysis was performed,[49,50] Lorentz and polarization corrections applied and data reduced to $|F_o|$-values.

Structures were solved by direct methods using the program SHELXS86[51] and Fourier synthesis. Isotropic least-squares refinements were performed using SHELX76[52] and empirical absorption correction was applied.[53] Maximum and minimum correction factors have been deposited at CCDC.

Further anisotropic refinements followed by a difference Fourier synthesis allowed to locate most hydrogen atoms, only a few were geometrically placed and refined riding on their parent C-atom. Positional and anisotropic thermal parameters of the non-hydrogen atoms were refined and all hydrogen atoms refined isotropically. Function $\Sigma w(F_o - F_c)^2$, $w = 1/[\sigma^2(F_o) + gF_o^2]$ with $\sigma(F_o)$ was minimized from counting statistics. Atomic scattering factors were taken from International Tables for X-ray Crystallography.[54] Plots were made with the EUCLID Package[30] and geometrical calculations with PARST.[55] All calculations were performed on a MicroVax-3400 at the Scientific Computer Center, University of Oviedo.*

Acknowledgements

One of us (B. O.) acknowledges a grant from the *Universidad Complutense de Madrid*.

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* Lists of structure amplitudes, anisotropic thermal parameters, H-atom parameters, distances and angles involving H-atoms, distances, angles and least-squares-planes data, principal torsion angles and X-ray crystallographic parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details of the deposition scheme, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1993, issue 1.

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Paper 3/01398G
Received 9th *March* 1993
Accepted 22nd *April* 1993