The Structure of N^1-Hydroxylophine N^3-Oxide (= 1-Hydroxy-2,4,5-triphenyl-1*H*-imidazole 3-Oxide) in the Solid State

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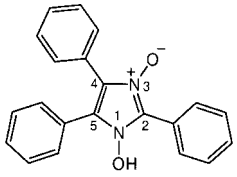
Dedicated to Professor *Jack D. Dunitz* on the occasion of his 80th birthday

The crystal structure of *1-hydroxy-2,4,5-triphenyl-1*H*-imidazole 3-oxide* (**1**) has been determined from laboratory X-ray powder-diffraction data. The two independent molecules in the asymmetric unit form chains *via* O–H···O hydrogen bonds related by a twofold screw axis. One of the O···O distances is extremely short (2.32(1) and 2.43(1) Å). Solid-state NMR spectroscopy (CPMAS) combined with calculation of absolute shieldings (GIAO/B3LYP/6-31G*) allowed us to determine that the compound behaves as if the O–H···O hydrogen bond has the proton in the middle (single-well potential), resulting in the near identity of both ^{15}N-NMR signals.

1. Introduction. – *Lettau* [1] reported that N^1-hydroxy-1*H*-imidazole N^3-oxides, like **1** (= 1-hydroxy-2,4,5-triphenyl-1*H*-imidazole 3-oxide or N^1-hydroxylophine N^3-oxide, described earlier by *Zimmermann* and co-workers [2]) show very strong H-bonds in the solid state. This conclusion was based on previous IR studies. Molecule **1** has been reported once since then and only to describe its behavior in HPLC [3].



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In search of molecules that could present intermolecular solid-state proton transfer (ISSPT) [4], we fixed our attention on **1**. The ISSPT phenomena require as necessary conditions strong H-bonds and identical (or very similar) energies before and after the proton transfer. The two classical examples are benzoic acid dimers (double proton

transfer) [5] and pyrazole dimers, trimers, and tetramers (two, three, or four proton transfers) [6]. Therefore, a subsidiary condition is a cyclic motif with a limited number of protons involved. In catemers, ISSPT is not observed, although the case of imidazole (a catemer) has raised much interest [7][8]. 1,2,4-Triazoles having both N-atoms in 1,2- and 1,4-positions behave in some cases like pyrazoles [9] and in other cases like imidazoles [10].

Compound **1** is a promising candidate to observe ISSPT in a catemer due to its reported strong H-bonds. A multiple proton transfer along the H-bonds or, at least, a new example of a centred O···H···O H-bond could be expected. The study will need the concomitant use of X-ray crystallography and solid-state NMR (CPMAS) to eventually distinguish between static and dynamic disorder [11].

2. Results and Discussion. – 2.1. *Crystallography.* Compound **1** was prepared according to *Zimmermann* and co-workers [2]. All our attempts to grow a single crystal of suitable size for X-ray were unsuccessful. Therefore, structure solution from single-crystal diffraction data was not possible.

The atom-labelling scheme of 1-hydroxy-2,4,5-triphenyl-1*H*-imidazole 3-oxide (**1**) used in the crystallographic part is depicted in *Fig. 1*. There are no examples retrieved in the CSD [12] for N^1-hydroxyimidazole N^3-oxides. Many molecular crystal structures have been solved from powder-diffraction data by direct space methods [13] followed by *Rietveld* refinement [14] (for recent examples, see [13][15–18]). It was, therefore, decided to use this method to determine the structure of the lophine derivative **1**.

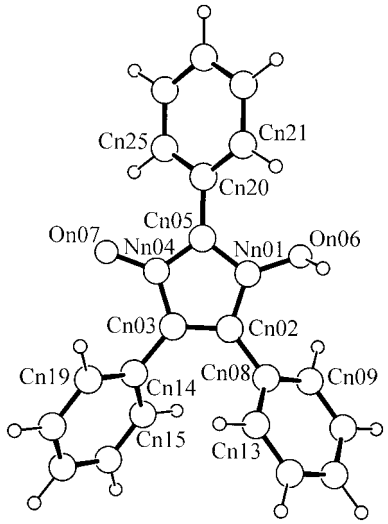


Fig. 1. *ORTEP* [37] *Diagram of molecule 1 of compound* **1** *showing the atomic numbering* ($n = 1$ or 2 for the independent molecules)

Compound **1** crystallizes with two independent molecules in the asymmetric unit. Selected geometric parameters with their restraints are given in *Table 1*. The restrained *Rietveld* refinement gave bond lengths and angles within expected ranges. The two

independent molecules present different conformations between the Ph rings and the central five-membered ring. While the three Ph rings in the molecule 1 are twisted in the same sense, in molecule 2 one of them (that corresponding to the Ph group at C(2) of the imidazole ring) is twisted in opposite sense (*Table 1*).

Table 1. *Selected Geometric Parameters* [Å, °]

	Restraint value	Calculated			Restraint value	Calculated	
		$n=1$	$n=2$			$n=1$	$n=2$
N(n01)–C(n02)	1.37(2)	1.367(5)	1.366(5)	N(n04)–C(n05)–N(n01)	107(2)	106.6(3)	106.6(3)
C(n02)–C(n03)	1.37(2)	1.358(5)	1.364(5)	C(n05)–N(n01)–O(n06)	123(2)	123.5(4)	122.7(5)
C(n03)–N(n04)	1.38(2)	1.369(6)	1.377(6)	C(n02)–N(n01)–O(n06)	127(2)	126.8(4)	127.0(5)
N(n04)–C(n05)	1.35(2)	1.346(6)	1.346(6)	N(n01)–C(n02)–C(n08)	123(2)	124.8(4)	122.2(4)
C(n05)–N(n01)	1.37(2)	1.376(5)	1.366(6)	C(n03)–C(n02)–C(n08)	131(2)	129.1(4)	131.8(4)
N(n01)–O(n06)	1.33(2)	1.324(6)	1.326(6)	C(n02)–C(n03)–C(n14)	129(2)	127.7(4)	129.3(4)
C(n02)–C(n08)	1.46(2)	1.454(5)	1.447(5)	N(n04)–C(n03)–C(n14)	122(2)	123.3(4)	122.1(4)
C(n03)–C(n14)	1.46(2)	1.454(5)	1.448(5)	C(n03)–N(n04)–O(n07)	127(2)	127.5(5)	127.8(5)
N(n04)–O(n07)	1.28(2)	1.278(6)	1.277(6)	C(n05)–N(n04)–O(n07)	123(2)	123.9(5)	123.4(5)
C(n05)–C(n20)	1.46(2)	1.458(5)	1.457(5)	N(n04)–C(n05)–C(n20)	127(2)	127.0(4)	127.6(4)
C(n05)–N(n01)–C(n02)	110(2)	109.6(3)	110.3(3)	N(n01)–C(n05)–C(n20)	126(2)	126.4(4)	125.7(4)
N(n01)–C(n02)–C(n03)	106(2)	106.1(3)	105.9(3)	N(n01)–C(n02)–C(n08)–C(n09)		–48.7	–52.2
C(n02)–C(n03)–N(n04)	109(2)	109.0(3)	108.4(3)	C(n02)–C(n03)–C(n14)–C(n15)		–49.7	–36.8
C(n03)–N(n04)–C(n05)	109(2)	108.6(4)	108.8(4)	N(n01)–C(n05)–C(n20)–C(n21)		–36.8	36.6

The molecules of compound **1** form H-bonded chains extending in the *c* axis, (*Fig. 2*). The O···O distances between the O-atoms involved in the H-bonds are 2.32(1) and 2.43(1) Å for each independent molecule. The projection along this axis (*Fig. 3*) shows hexagonal packing of chains (catemer). These chains interact with neighboring chains related by a glide plane through hydrophobic contacts between the Ph rings forming the 3D-crystal (C(211)–H(211)···Centroid$_{(C(214–219))ring}$($x-1/2,3/2-y,z$) = 3.849 Å, C(217)–H(217)···Centroid$_{(C(208–213))ring}$($1/2+x,3/2-y,z$) = 3.897 Å and C(117)–H(117)···Centroid$_{(C(220–225))ring}$($1/2+x,1/2-y,z$) = 4.087 Å).

The symmetry imposed by *Pna*2$_1$ means that disorder of the H-atom involved in H-bonding is possible but not necessary (see *Experimental Part*). The final result is somewhat contradictory. If one compares the two molecules, the N–O distances are almost identical for the two independent molecules but show distinct values: 1.28 Å for the $N^+–O^-$ and 1.33 Å for the N–OH. On the other hand, the O···O distances (2.32(1) and 2.43(1) Å) are extremely short.

An examination of the literature concerning short and strong O–H···O H-bonds shows that the shortest O···O distances reported are 2.39 Å and correspond to symmetric (or centred) $[O\cdots H\cdots O]^-$ H-bonds [19][20] (low-temperature neutron-diffraction studies of organic molecules). A survey of the CSD [10] for O···O distances shorter than 2.39 Å and containing no errors yield two compounds: *trans*-bis(ethylenediamine)hydrogendiacetatocobalt(III) diperchlorate monohydrate (TENACU) with d_{OO} = 2.37(1) Å (C=O^-···H···$^-$O=C) [21] and a trichloro-bridged diruthenium(III,III) complex (MIJCOX) with d_{OO} = 2.387(5) Å [22]. This second example is related to ours, because it corresponds to $[Ph_3P{=}O\cdots H\cdots O{=}PPh_3]^+$.

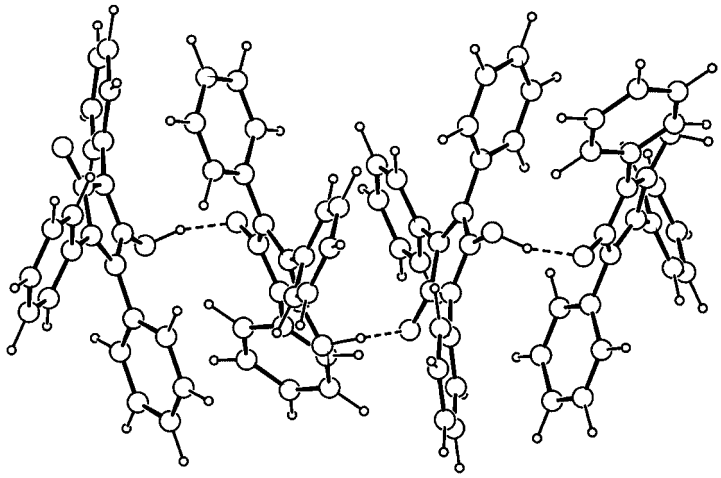


Fig. 2. *View of a H-bonded chain for compound* **1** *showing extension in* c*-axis direction*

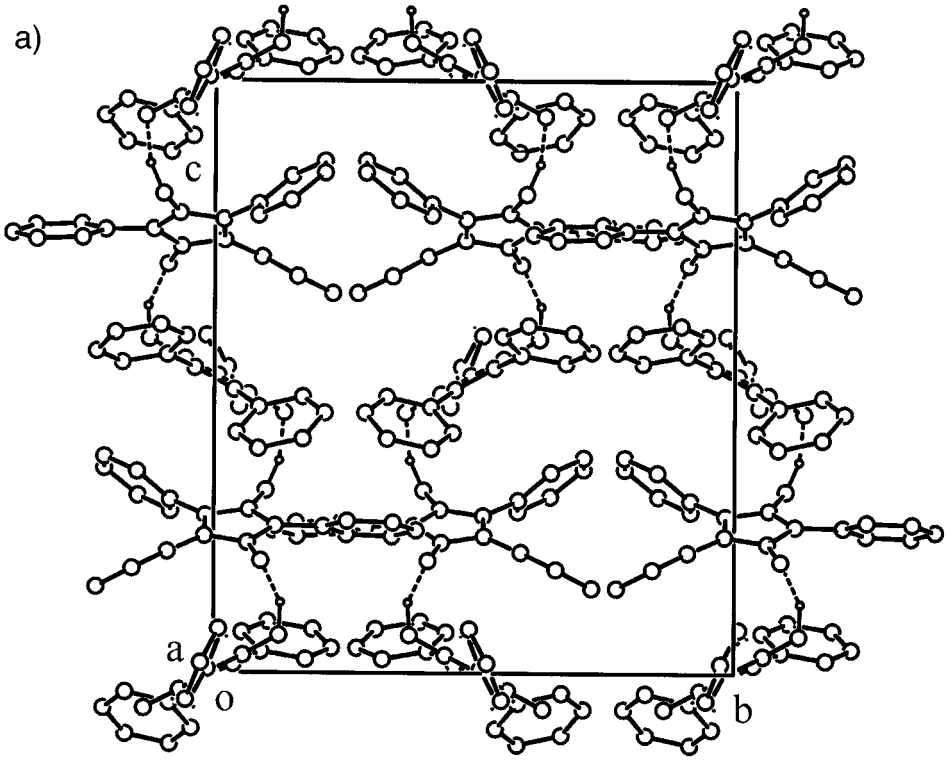


Fig. 3. *Packing diagram for* **1**: a) a*-axis projection*, b) c*-axis projection*. H-atoms are omitted for clarity.

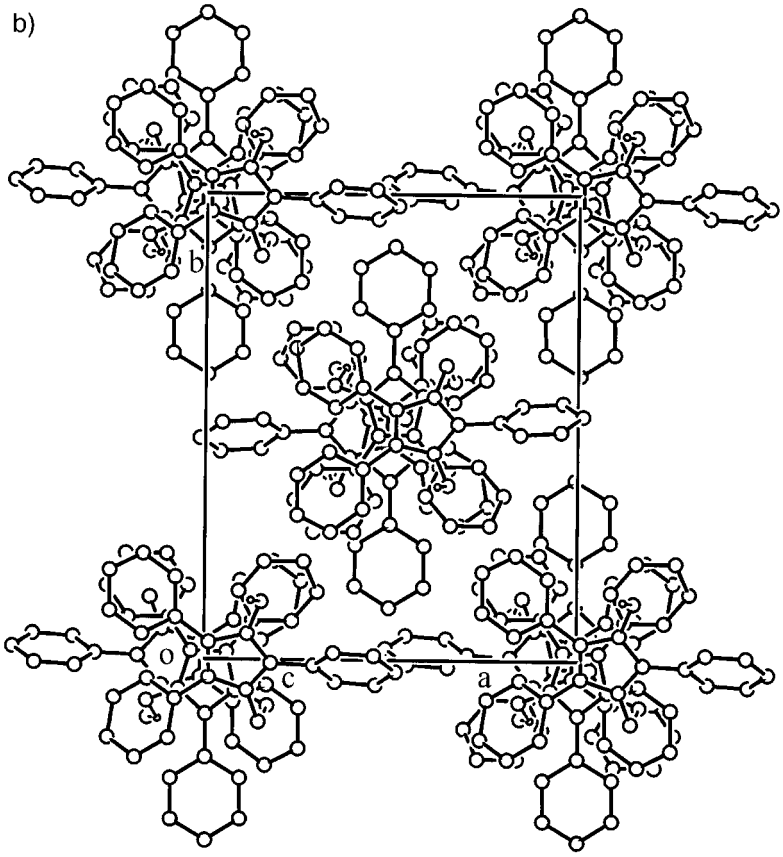


Fig. 3 (cont.)

Since the proton in the (N–O···H···O–N) bridge cannot be localized with certainty from the powder X-ray data, the O···O distances, 2.43(1) but mainly 2.32(1) Å, should correspond to a very distorted (as represented, with OHO angles of 161.4 and 135.7°, resp.) or to more-linear situations with the proton in the middle. In any case, compound **1** appears to be asymmetric but forms very strong H-bonds even assuming that the 2.32 Å distance has been underestimated in the refinement.

2.2. *NMR Spectroscopy.* In $CDCl_3$ solution, both ^{1}H- (400 MHz) and ^{13}C-NMR (100 MHz) data (*Tables 2* and *3*) correspond to a prototropic equilibrium between two identical tautomers **1a** and **1b** (autotrope or degenerate). The proton transfer is slow, even at room temperature (300 K), and some signals are broad or, in some cases, not even observed. At 233 K, all signals are found. The addition of a very small amount of CF_3COOH increases considerably the rate, and narrow average signals are observed, formally corresponding to **1c**.

The ^{1}H-NMR results (*Table 2*) have been used to assign the ^{13}C signals through different 2D experiments (see *Exper. Part*). The assignment of the 4- and 5-Ph chemical

Table 2. *^{1}H-NMR Chemical Shifts of 1-Hydroxy-2,4,5-triphenyl-1*H*-imidazole 3-oxide* (**1**)

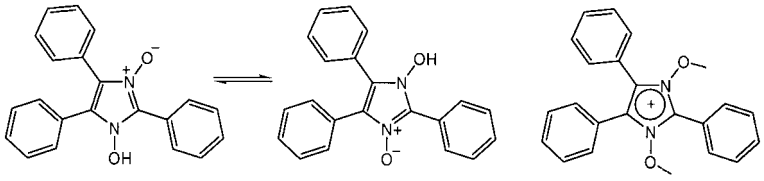
	OH	2-Ph			4-Ph			5-Ph		
		ortho	*meta*	*para*	*ortho*	*meta*	*para*	*ortho*	*meta*	*para*
$CDCl_3$, 233 K	11.91	8.22	7.33	7.45	7.62[a])	7.45	7.45	6.44[b])	7.07	7.25
Average	–	8.22	7.33	7.45	7.03	7.26	7.35	7.03	7.26	7.35
$CDCl_3$, 300 K	–	8.31	7.33	7.44	7.61	7.44	7.44	6.60	7.08	7.23
$CDCl_3 + CF_3COOH$	–	7.98	7.34	7.42	7.06	7.25	7.32	7.06	7.25	7.32

[a]) Correlated through a gs-HMBC experiment with the signal at 129.5 ppm (C(4) in *Table 3*). [b]) Correlated through a gs-HMBC experiment with the signal at 126.4 ppm (C(5) in *Table 3*).

Table 3. *^{13}C-NMR Chemical Shifts of 1-Hydroxy-2,4,5-triphenyl-1*H*-imidazole 3-oxide* (**1**)

	C(2)	C(4)	C(5)	2-Ph				4-Ph				5-Ph			
				ipso	*ortho*	*meta*	*para*	*ipso*	*ortho*	*meta*	*para*	*ipso*	*ortho*	*meta*	*para*
$CDCl_3$, 233 K	135.4	129.5[a])	126.4[b])	119.9	130.1	128.7	131.1	123.9	130.0	128.6	129.4	123.7	129.2	127.8	128.8
Average	135.4	128.0	128.0	119.9	130.1	128.7	131.1	123.8	129.6	128.2	129.1	123.8	129.6	128.2	129.1
$CDCl_3$, 300 K	135.7	n.o.	n.o.	120.6	130.4	128.8	131.1	124.4	130.1	128.6	129.8	124.4	129.5	127.9	128.0
$CDCl_3 + CF_3COOH$	135.5	126.3	126.3	120.9	130.0	128.7	131.0	124.6	130.0	128.3	129.2	124.6	130.0	128.3	129.2
CPMAS 300 K	132.5[c])	128.6[c])	126.6[c])	121.1[c])	130.0 121.8[c])	128.6	130.0	124.7[c])	130.0	128.6	130.0	123.2[c])	130.0	127.7	128.5

[a]) Correlated with the signal at 7.62 ppm (H_{ortho} of 4-Ph in *Table 2*). [b]) Correlated with the signal at 6.44 ppm (H_{ortho} of 5-Ph in *Table 2*). [c]) Quaternary C-atoms (NQS experiment).



1a **1b** **1c**

shifts was achieved by comparing them to calculated values (see later) and through gs-HMBC experiments (see *Footnotes* in *Tables 2* and *3*). Note that the average of the signals obtained at 233 K are very close to the values measured with a small amount of CF_3COOH. Note also that the *ortho* protons of the 2-Ph group are very sensitive to the temperature and to the acidity of the medium.

The conclusions arising from the ^{13}C-NMR study of **1** in $CDCl_3$ (*Table 3*) are in total agreement with those derived from ^{1}H-NMR: no tautomerism at 233 K (narrow signals due to **1a**), slow prototropy at 300 K (broad signals), rapid exchange in the presence of CF_3COOH, and similarity of the calculated average chemical shifts to those of the acidified solution (structure **1c**).

The ^{13}C-NMR spectrum of **1** has been recorded in the solid state (CPMAS) at 100 (9.4 T) and 50 MHz (4.7 T) at 300 K, in standard conditions and with a nonquaternary suppression NQS experiment (only quaternary C-atoms are observed); the standard spectrum at 100 MHz is represented in *Fig. 4* (that obtained at 50 MHz is identical).

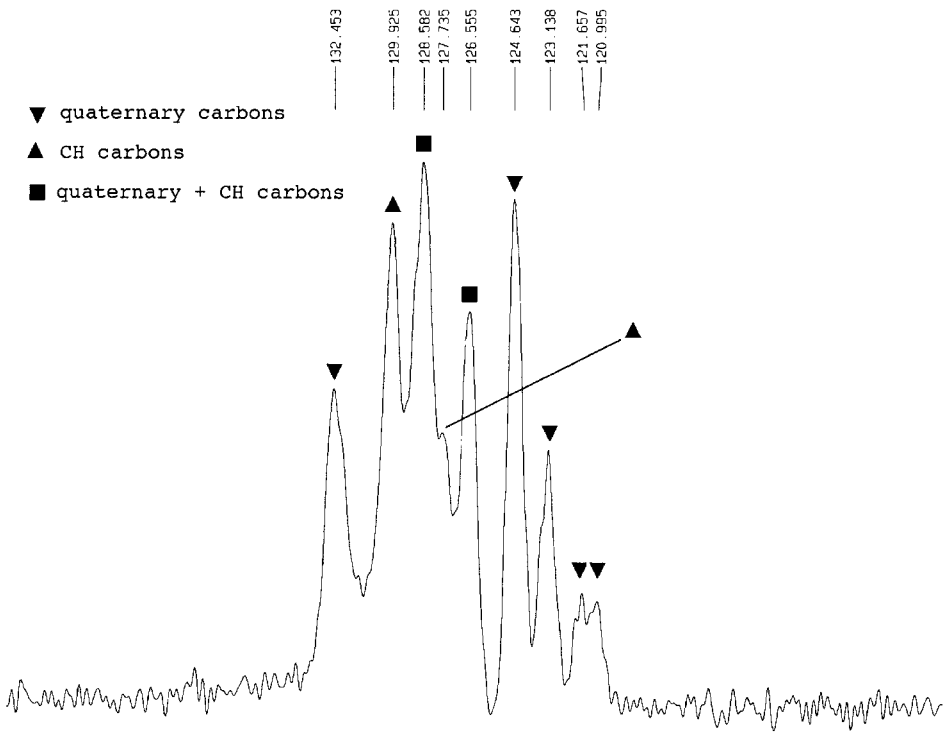


Fig. 4. *^{13}C-CPMAS-NMR Spectrum of* **1** (100.73 MHz, 300 K)

This spectrum, according to the chemical shifts, seems to match the spectrum in $CDCl_3$ at 233 K, that is, to a blocked prototropy situation, **1a**. We have to consider that there are two different molecules in the crystal. This explains some splittings, like that of C_{ipso} of the 2-Ph group. However, the CPMAS ^{13}C-NMR spectrum could also be consistent with the average spectrum in solution, **1c**, assuming that some splittings are due to the presence of two molecules and/or to the nuclear quadrupole effects of the ^{14}N atoms [23].

Therefore, we turned our attention to ^{15}N-NMR spectroscopy. Compound **1** is not very soluble in most common solvents; for this reason, we have not been able to measure its ^{15}N chemical shifts in solution (and even more at the low temperatures required to block the tautomerism). In the solid state at 300 K (*Fig. 5*), two very narrow lines at -170.4 and -166.2 ppm ($\Delta\delta = 4.2$ ppm, average -168.3 ppm) are observed. When the temperature is lowered to 200 K, the spectrum remains unchanged.

Does this spectrum correspond to **1a** or to **1c**? There are no NMR literature data on N^1-hydroxy-1*H*-imidazole N^3-oxides, and so we have recorded the ^{15}N-CPMAS/NMR spectrum of 1-(4-methylphenyl)-1*H*-imidazole 3-oxide (**2**), a compound described in an earlier paper [24].

Two signals are observed at -205.6 (*N*-tolyl) and -130.5 ppm (*N*-oxide). This is a first indication that -168.3 ppm cannot be a signal from **1a**, but still our question

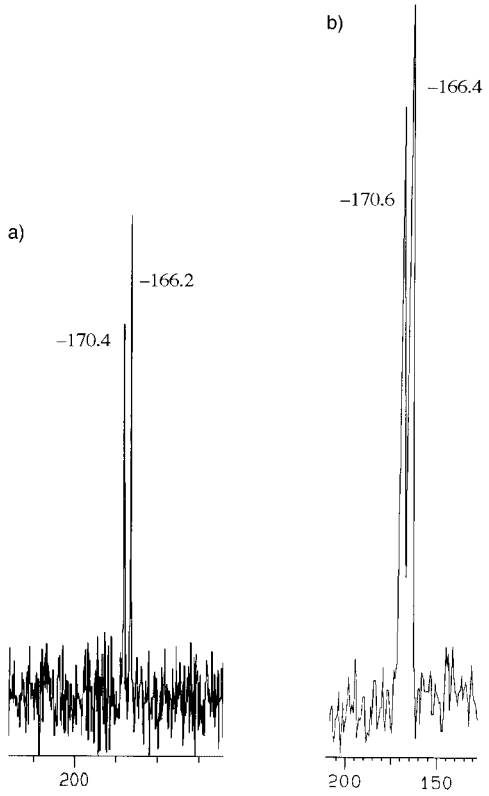
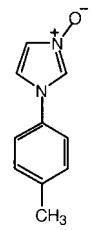


Fig. 5. *^{15}N-CPMAS NMR Spectrum of* **1** *at* a) *40.59 MHz and* b) *20.28 MHz at 300 K*



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remains unanswered. Trying to shed additional light onto the problem, we decided to do some theoretical calculations.

2.3. *Theoretical Calculations.* To have an estimate of the geometry of the isolated lophine **1**, we have carried out B3LYP/6-31G* calculations on the two geometries of the monomer related to those determined experimentally, that is, with torsion angles of -36.8 (2-Ph), -49.7 (4-Ph) and $-48.7°$ (5-Ph, molecule 1; *Table 1*) and $+36.6$ (2-Ph), -36.8 (4-Ph) and $-52.2°$ (5-Ph, molecule 2; *Table 1*). Only the geometry with $+/-/-$ angles is a minimum (the other reverts to the first one on the optimisation process): $+19.3°$ (2-Ph), $-33.8°$ (4-Ph) and $-41.2°$ (5-Ph).

The three more-relevant distances of the monomer are O(n07)–N(n04) = 1.285 Å, N(n01)–O(n06) = 1.388 Å, and O(n06)–H = 0.978 Å. The H-bond present in the crystal does not modify the N^+-O^- distance (1.28 Å) but shortens the N–OH distance (1.33 *vs.* 1.39 Å) compared with the gas-phase isolated molecule at 0 K.

Then, we performed GIAO calculations on the optimized geometry of **1a** (GIAO/B3LYP/6-31G*; see *Exper. Part*). The ^{1}H and ^{13}C absolute shieldings have been used only to assign the signals of the 4-Ph and 5-Ph rings and those of the C-atoms C(4) and C(5) of the 1*H*-imidazole moiety. But, clearly the most interesting part concerns ^{15}N-NMR. Since, at this level of the theory, only relative shieldings can be expected [25], we need a series of experimental δ and calculated σ values to establish an empirical relationship. These data are collected in *Table 4*.

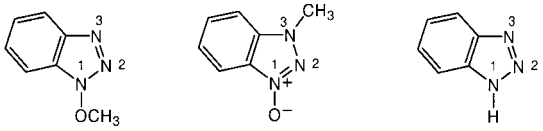


Table 4. *^{15}N-NMR Absolute Shielding and Chemical Shifts of Selected Compounds* (all in ppm)

Compound/Atom	σ (GIAO)	δ (MeOH)	δ (acetone)	δ (DMSO)	Ref.	δ (CPMAS)
2/N(1)	103.46	–	–	–		– 205.6
2/N(3)	– 25.95	–	–	–		– 130.5
3/N(1)	– 10.17	– 116.7	– 116.1	– 112.3	[26]	–
3/N(2)	– 111.95	– 20.2	– 16.8	– 14.7	[26]	–
3/N(3)	– 78.92	– 63.2	– 52.9	– 50.9	[26]	–
4/N(1)	– 58.20	– 88.6	– 76.9	– 74.8	[26]	–
4/N(2)	– 77.43	-47.5	– 48.0	– 44.7	[26]	–
4/N(3)	99.73	– 205.7	– 215.5	– 208.0	[26]	–
5/N(1)	51.02	–	– 177.0	– 168.0	[27]	– 157.6
5/N(2)	– 117.47	–	– 15.0	0.0	[27]	– 11.8
5/N(3)	– 90.79	–	– 43.0	– 27.0	[27]	– 56.4
1a/N(1) (N–OH)	80.98	– 193.3	– 201.7	– 195.3		– 191.5
1a/N(3) (N^+-O^-)	– 12.28	– 113.6	– 114.2	– 107.5		– 115.4
1c/N(1/3) average	34.35	– 153.4	– 157.9	– 151.4		– 153.5
6a (anion)	2.02	–	–	–		– 127.1
6c (cation)	57.54	–	–	–		– 172.4
6 average	29.78	–	–	–		– 149.7

A regression of the experimental data against the calculated values yields four equations and the estimated chemical shifts for **1a**, already incorporated in *Table 4*.

$$\delta\ (\mathrm{MeOH}) = -(124 \pm 5)\ -\ (0.86 \pm 0.06),\ n = 6,\ r^2 = 0.980$$

$$\delta\ (\mathrm{acetone}) = -(126 \pm 2) - (0.94 \pm 0.02),\ n = 9,\ r^2 = 0.997$$

$$\delta\ (\mathrm{DMSO}) = -(119 \pm 3) - (0.94 \pm 0.03),\ n = 9,\ r^2 = 0.993$$

$$\delta\ (\mathrm{CPMAS}) = -(125 \pm 9) - (0.82 \pm 0.10),\ n = 5,\ r^2 = 0.953$$

According to these calculations, two ^{15}N signals at -115 and -191 ppm ($\Delta\delta = 76$ ppm) for **1a**, and a unique one at -154 ppm for the average situation **1c** should be expected. The observation of two signals at -170.4 and -166.2 ppm ($\Delta\delta = 4.2$ ppm, average -168.3 ppm) is consistent with **1c**, the splitting being due to the existence of two independent molecules in the asymmetric unit. In some dynamic prototropic processes studied by ^{15}N-NMR in the solid state, two close signals are observed at the coalescence [28]. This is due to a difference in the population of the two forms in equilibrium, identical when isolated, but slightly different in the crystal. In this case, lowering the temperature results in a separation and broadening of the two lines [28]. In the case of **1**, a lowering of 100 degrees or the use of another field (from 4.7 to 9.4 T), does not modify the spectrum (*Fig. 5*).

2.4. *Comparison of the Three Methods.* When discussing the study of degenerate proton transfer between identical tautomers by NMR in the solid state, three limit situations should be considered (*Fig. 6*). Situation *I* corresponds to the very common case where the barrier is too high to observe the proton transfer *within the NMR observational window* (it can correspond to static disorder in crystallography [11]). The intermediate case *II* corresponds to the temperature-dependent dynamic behavior that can be studied by NMR [4–6][9], and that we have named ISSPT (the transfer often has a tunnelling component and corresponds to dynamic disorder in crystallography). If the distance between the heavy atoms is very short, then the situation will correspond to a single-well potential *III*. In this case, there will be no disorder in the crystallography, and nothing dynamic in the NMR. We propose that the crystals of compound *1* we have obtained (other polymorphs may behave differently) are consistent only with case *III*.

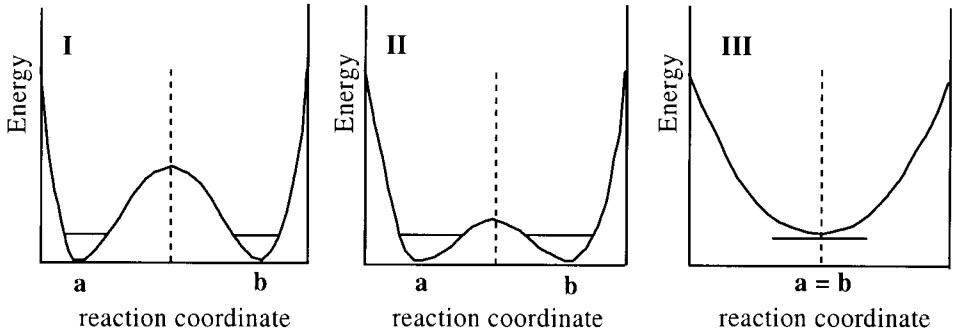
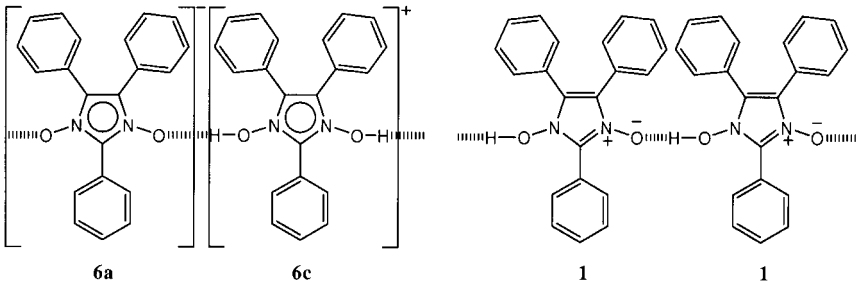


Fig. 6. *Energy profiles for proton transfer in degenerate situations*

The strong H-bond acceptor properties of amine *N*-oxides are well-documented [29]. On the other hand, the H-bond donor properties of the *N*-OH moiety are not known, but they can be inferred from the pK_a of 1-hydroxy-2,4,5-triphenyl-1*H*-imidazole ($pK_a = 8.39$ [30], phenol, $pK_a = 9.9$ [31]). The presence of a positive charge in the 1*H*-imidazole ring should make **1** much more acidic than **6**, and so it would be expected to behave as a very strong H-bond donor. Therefore, compound **1** is simultaneously a strong donor and a strong acceptor of H-bonds. It cannot be excluded

that, in some cases, a single proton transfer occurs between two adjacent molecules to afford an imidazolate **6a**/imidazolium **6c** salt.

In the present case, due to the very short O ··· O distances, the difference between a chain of neutral molecules **1** and a chain of salts **6a**/**6c** blurred, and we could not decide between these two possibilities. According to data in *Table 4*, to the average situation **6** for **6a**/**6b** corresponds a ^{15}N chemical shift of -149.7 ppm, which is both close to the average of ^{15}N signals of **1c** (-153.5 ppm) and to the experimental result (-168.3 ppm).



6a **6c** **1** **1**

Conclusions. – The powder-diffraction method is a useful tool in cases where a suitable single crystal cannot be obtained. We find that the solid-state structure of compound **1** comprises columnar stacks of the molecules joined through O–H ··· O intermolecular H-bonds, and that these columns display a hexagonal arrangement permitting intermolecular Ph contacts. Structurally, compound **1** shows a very rare case of a centered H-bond, which confers unusual NMR properties.

We are grateful *to Alastair Florence* of the Deptartment of Pharmaceutical Sciences, Strathclyde University, Glasgow, for collecting the diffraction data. *Lourdes Infantes* acknowledges the *Ministerio de Educación y Cultura* of Spain for a postdoctoral fellowship. *Harriott Nowell* is grateful to the *CCDC* and the *EPSRC* for a studentship. Thanks are also given to the MCyT/DGI of Spain (Project Numbers BQU 2000-0252 and BQU 2001-1095) for financial support.

Experimental Part

Since the compound is not very soluble, a sat. EtOH soln. was filtered over a fritted filter, and crystals were obtained by slow evaporation.

*Crystallographic Data Collection and Structure Determination of 1-Hydroxy-2,4,5-triphenyl-1*H*-imidazole 3-Oxide* (**1**). A summary of data collection and refinement procedures is given in *Table 5*. The crystal structure of the title compound has been determined from laboratory powder-diffraction data with the DASH program [32][33], which implements a simulated annealing method of structure solution. The data were indexed with DICVOL [34], an orthorhombic cell (lattice parameters $a = 12.6711$, $b = 15.7661$, $c = 17.8909$ Å) was indicated with figures of merit $F(20) = 22.9$ and $M(20) = 59.1$. An examination of systematic absences [35] indicated space group $Pna2_1$, which gave a good fit between observed and calculated data ($\chi 2_{Pawley} = 1.85$). Subsequent simulated annealing with intensities extracted in this refinement resulted in a crystal structure with no unfavorable close contacts and $\chi 2_{\text{Profile}} = 7.81$. The space group could not be assigned unambiguously, but results of simulated annealing runs with other space groups gave unlikely crystal structures with unfavorable close contacts. The symmetry imposed by $Pna2_1$ means that disorder of the H-atom involved in H-bonding is possible but not necessary. Restrained *Rietveld* refinements were carried out with GSAS [36]. Compound **1** and other N^1-hydroxy-1*H*-imidazole N^3-oxides are absent in the CSD, so initial distance and angle restraints, as listed in *Table 1*, were adjusted during refinement, starting with best estimates from similar CSD structures. In one of the

last stages of the refinement, the isotropic thermal parameters for the C-, N- and O-atoms were refined with a common U_{iso} parameter for each 'group'. The H-atoms were fixed in the last cycles of refinement to reduce the number of parameters. The final fit between observed and calculated diffraction patterns is shown in *Fig. 7*. Drawings were made with ORTEP [37].

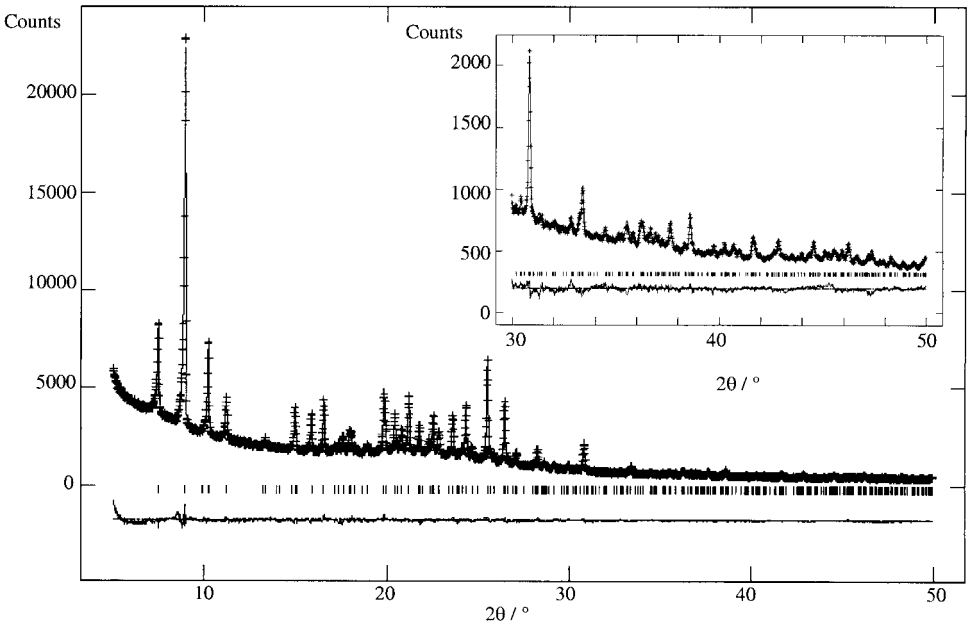


Fig. 7. *The* Rietveld *plot showing the observed and difference profiles for* **1**. The tick-marks for reflection positions are shown above the difference profile.

Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the *Cambridge Crystallographic Data Centre* as deposition No. CCDC-198894. Copies of the data can be obtained, free of charge, on application to the CCDC, 12 Union Road, Cambridge CB2 1EZ UK (fax: +44 (1223) 336033; e-mail: deposit@ccdc.cam.ac.uk).

NMR Experiments. ^{1}H- (400.13 MHz) and ^{13}C-NMR (100.61 MHz) spectra in soln. were obtained with a *Bruker DRX-400* instrument at 233 and 300 K. 2D-Inverse-proton-detected homonuclear-shift-correlation spectra gs-COSY, and heteronuclear-shift-correlation spectra gs-HMQC and gs-HMBC were obtained with the standard pulse sequences [38]. Solid-state ^{13}C- (100.73 MHz) and ^{15}N- (40.59 MHz) CPMAS-NMR spectra have been obtained with a *Bruker WB-400* spectrometer at 200 and 300 K with a wide-bore 4-mm DVT probehead at rotational frequencies of *ca.* 5–6 kHz. Samples were carefully packed in ZrO_2 rotors, and the standard CPMAS pulse sequence and NQS technique (Non Quaternary Suppression to observe only the quaternary C-atoms) were employed [38]. Chemical shifts (δ) [ppm] are relative to Me_4Si, and $^{15}NH_4Cl$ (these were converted to $MeNO_2$ according to the relationship. δ ($^{15}N(MeNO_2) = \delta(^{15}N(NH_4Cl)) - 338.1$ ppm). In several cases, solid state ^{13}C- (50.32 MHz) and ^{15}N- (20.28 MHz) CPMAS-NMR spectra have been obtained with a *Bruker AC-200* spectrometer at 298 K with a 7-mm *Bruker DAB 7* probehead that achieves rotational frequencies of *ca.* 3.5–4.5 kHz.

DFT Calculations. The optimization of the structures of all compounds discussed in this paper was carried out at the B3LYP/6-31G* level [39][40] by the facilities of the Gaussian98 set of programs [41]. In all cases, the minimum nature of the geometries has been confirmed by frequency calculations at the same level. Absolute shielding σ were calculated, at the same level, over these geometries within the GIAO approximation [42][43].

Table 5. *Summary of Data Collection and Refinement for Compound* **1**

Crystal Data					
Chemical formula		$C_{21}H_{16}N_2O_2$	Lattice Parameters		
Formula weight		328.36	a [Å]		12.6866(6)
Crystal system		orthorhombic	b [Å]		15.7706(8)
Space group		$Pna2_1$	c [Å]		17.8983(4)
Z		8	V [Å^3]		3581.0(3)
ρ_{calc} [g cm^{-3}]		1.22			
Data collection					
Diffractometer		*Bruker AXS D8*			
$2\theta_{min}$ [°]		5	Wavelength [Å]		1.5406
$2\theta_{max}$ [°]		50.002	No. of reflections		343
Step size [°]		0.014	No. of observations (profile points)		3104
Refinement					
Bond-length-restraint observations (weight factor)				90 (20)	
Angle-length-restraint observations (weight factor)				140 (20)	
Planar-group-restraint observations (weight factor)				8 (3)	
U_{iso} [Å^2]	C	0.01919	No. of Parameters	Profile	22
	O	0.08697	Atom	149	
	N	0.06028			
R_{wp}		0.0349	R_F^2		0.0988
R_p		0.0268	Reduced-χ^2		2.043

REFERENCES

[1] H. Lettau, *Z. Chem*. **1970**, *10*, 211.
[2] K. Volkamer, H. Baumgärtel, H. Zimmermann, *Angew. Chem., Int. Ed*. **1967**, *6*, 947; K. Volkamer, H. W. Zimmermann, *Chem. Ber*. **1969**, *102*, 4177.
[3] M. M. Dávila-Jiménez, M. P. Elizalde-González, S. García-Díaz, *J. Liq. Chromatogr*. **1998**, *21*, 1629.
[4] A. L. Llamas-Saiz, C. Foces-Foces, C. Fontenas, N. Jagerovic, J. Elguero, *J. Mol. Struct*. **1999**, *484*, 197.
[5] B. H. Meier, F. Graf, R. R. Ernst, *J. Chem. Phys*. **1982**, *76*, 768.
[6] J. A. S. Smith, B. Wehrle, F. Aguilar-Parrilla, H.-H. Limbach, M. C. Foces, F. H. Cano, J. Elguero, A. Baldy, M. Pierrot, M. M. T. Khurshid, J. B. Larcombe, *J. Am. Chem. Soc*. **1989**, *111*, 7304.
[7] J. L. Brédas, M. P. Poskin, J. Delhalle, J. M. André, H. Chojnacki, *J. Phys. Chem*. **1984**, *88*, 5882.
[8] W. Münch, K.-D. Kreuer, W. Silvestri, J. Maier, G. Seifert, *Solid State Ionics* **2001**, *145*, 437.
[9] M. A. García, C. López, O. Peters, R. M. Claramunt, O. Klein, D. Schagen, H.-H. Limbach, C. Foces-Foces, J. Elguero, *Magn. Reson. Chem*. **2000**, *38*, 604.
[10] R. M. Claramunt, C. López, M. A. García, M. D. Otero, M. R. Torres, E. Pinilla, S. H. Alarcón, I. Alkorta, J. Elguero, *New J. Chem*. **2001**, *25*, 1061.
[11] M. C. Etter, R. C. Hoye, G. M. Vojta, *Cryst. Rev*. **1988**, *1*, 281.
[12] F. H. Allen, *Acta Crystallogr.*, *Sect B* **2002**, *58*, 380.
[13] W. I. F. David, K. Shankland, L. B. McCusker, C. Baerlocher, 'Structure Determination from Powder Diffraction Data', Oxford University Press, 2002.
[14] H. M. Rietveld, *J. Appl. Crystallogr.* **1969**, *2*, 65.
[15] E. Y. Cheung, E. E. McCabe, K. D. M. Harris, R. L. Johnston, E. Tedesco, K. M. P. Raja, P. Balaram, *Angew. Chem., Int. Ed.* **2002**, *41*, 494.
[16] H. Nowell, J. P. Attfield, J. C. Cole, P. J. Cox, K. Shankland, S. J. Maginn, W. D. S. Motherwell, *New J. Chem.* **2002**, *26*, 469.
[17] S. Pagola, P. W. Stephens, D. S. Bohle, A. D. Kosar, S. K. Madsen, *Nature* **2000**, *404*, 307.
[18] L. E. Ochando, J. M. Amigó, J. Rius, D. Louër, C. Fontenas, J. Elguero, *J. Mol. Struct*. **2001**, *562*, 11.
[19] T. Steiner, W. Saenger, *Acta Crystallogr., Sect. B* **1994**, *50*, 348.
[20] G. A. Jeffrey, 'An Introduction to Hydrogen Bonding', Oxford University Press, New York, 1997.
[21] J. Rozière, C. Belin, *Acta Crystallogr.*, *Sect B* **1979**, *35*, 2037.

[22] M. P. de Aruajo, S. L. Queiroz, A. A. Batista, E. H. Panepucci, G. Oliva, E. E. Castellano, *Transition Metal Chem.* **2002**, *27*, 110.
[23] S. H. Alarcón, J. A. Jiménez, R. M. Claramunt, H.-H. Limbach, J. Elguero, *Magn. Reson. Chem*. **2000**, *38*, 305.
[24] J. Alcázar, A. de la Hoz, M. Begtrup, *Magn. Reson. Chem*. **1998**, *36*, 296.
[25] I. Alkorta, J. Elguero, *Struct. Chem*. **2002**, *13*, 97.
[26] W. Schilf, L. Stefaniak, M. Witanoeski, G. A. Webb, *Magn. Reson. Chem*. **1985**, *23*, 181.
[27] N. Jagerovic, M. L. Jimeno, I. Alkorta, J. Elguero, R. M. Claramunt, *Tetrahedron* **2002**, *58*, 9089.
[28] R. M. Claramunt, D. Sanz, S. H. Alarcón, M. Pérez-Torralba, J. Elguero, C. Foces-Foces, M. Pietrzak, U. Langer, H.-H. Limbach, *Angew. Chem., Int. Ed*. **2001**, *40*, 420.
[29] I. Rozas, I. Alkorta, J. Elguero, *J. Phys. Chem. A* **1999**, *101*, 8861.
[30] S. O. Chua, M. J. Cook, A. R. Katritzky, *J. Chem. Soc. B* **1971**, 2350.
[31] 'Tables of Rate and Equilibrium Constants of Heterolytic Organic Reactions', Ed. V. A. Palm, Vol. I, Moscow, 1975.
[32] W. I. F. David, K. Shankland, N. Shankland, *Chem. Commun.* **1998**, 931.
[33] W. I. F. David, K. Shankland, J. Cole, S. Maginn, W. D. S. Motherwell, R. Taylor, 'DASH User Manual', Cambridge Crystallographic Data Centre, Cambridge, UK, 2001.
[34] A. Boultif, D. Louër, *J. Appl. Cryst.* **1991**, *24*, 987.
[35] A. J. Markvardsen, W. I. F. David, K. Shankland, *Acta Crystallogr.*, *Sect A* **2002**, *58*, 316.
[36] R. B. Von Dreele, A. C. Larson, 'General Structure Analysis System (GSAS)', Copyright, Regents of the University of California, 2001.
[37] L. J. Farrugia, *J. Appl. Crystallogr.* **1997**, *30*, 565.
[38] S. Braun, H.-O. Kalinowski, S. Berger, '150 and More Basic NMR Experiments', Wiley-VCH, 1998.
[39] P. A. Hariharan, J. A. Pople, *Theor. Chim. Acta* **1973**, *28*, 213.
[40] A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648; C. Lee, W. Yang, R. G. Parr, *Phys. Rev. B* **1988**, *37*, 785; A. D. Becke, *Phys. Rev. A* **1988**, *38*, 3098; B. Miehlich, A. Savin, H. Stoll, H. Preuss, *Chem. Phys. Lett*. **1989**, *157*, 200
[41] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A. Montgomery, R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. G. Johnson, W. Chen, M. W. Wong, J. L. Andres, M. Head-Gordon, E. S. Replogle, J. A. Pople, Gaussian98, *Gaussian*, *Inc*., Pittsburgh, PA, 1998.
[42] F. London, *J. Phys. Radium* **1937**, *8*, 397.
[43] R. Ditchfield, *Mol. Phys.* **1974**, *27*, 789.

Received February 3, 2003