Low barrier hydrogen bonds in sterically modified Schiff bases

Aleksander Filarowski,* Aleksander Koll and Tadeusz Glowiak

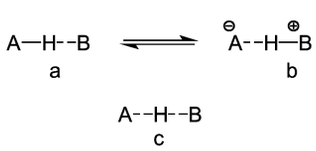
Faculty of Chemistry, University of Wroclaw, 14 F. Joliot-Curie str., 50-383, Wroclaw, Poland

Received (in Cambridge, UK) 11th July 2001, Accepted 18th February 2002
First published as an Advance Article on the web 6th March 2002

Five derivatives of an *ortho*-hydroxy Schiff base (2-(*N*-alkyl-α-iminoethyl)phenols) with very short intramolecular hydrogen bonds ($d_{O(H)\cdots N} \leq 2.500$ Å) were synthesised. The crystal structures were determined. The steric repulsion of the substituted methyl group results in an unusual strengthening of the hydrogen bonds, decreasing the barrier for the proton movement within the hydrogen bridge, which leads to a delocalization of the proton position. The very strong influence of the character of the substituent in the phenol ring as well as the character of the *N*-alkyl chain on the proton distribution is demonstrated for these hydrogen bonds from the so-called inversion range.

Introduction

The question of the symmetry of proton distribution in a hydrogen bond is an old one and still important in the understanding of the nature of this interaction. Usually a hydrogen bond is asymmetric with the hydrogen atom closer to a more basic atom **A** (see Scheme 1). When the hydrogen atom shifts to



Scheme 1

the acceptor atom **B**, the zwitterionic hydrogen bond is formed. If **A** and **B** atoms have similar basicity, the system still may be of lower energy when hydrogen is closer to either the **A** or **B** atom, than when centred between them and a double-well potential is formed. If the barrier between the minima is sufficiently low, the potential becomes a dynamically symmetric one.

Further increase of the hydrogen bond strength leads to the structure of **c** type where the hydrogen is centred between two atoms; its motion is described by a single-well potential. Such a hydrogen bond is often called a symmetric one.

Low barrier hydrogen bonds (LBHBs) appear when the distance between the **A** and **B** atoms is less than 2.55 Å for OHO and less than 2.65 Å for OHN hydrogen bonds. Both IR spectroscopy and X-ray crystallography show that the hydrogen atom is strongly delocalized in such hydrogen bonds.

Discussion on LBHBs has become more popular in recent years. The proton transfer along the chain of LBHBs is a rate-determining step in numerous enzymatic reactions in biological systems.[1] Scheiner *et al.* studied the influence of length and bending of the hydrogen bridge on the barrier height in the ground and excited states.[2,3] Cleland and Kreevoy,[4] and Frey[5] suggested that LBHBs have a covalent bonding contribution. According to Gilli *et al.*,[6] stabilization by resonance (in a Resonance Assisted Hydrogen Bond) permits overpassing of the steep increase of the interatomic repulsion term when the A ··· B distance is shortened and contributes to formation of a symmetrical and totally delocalized three-center four-electron covalent A ··· H ··· B bond. Such delocalization becomes a factor increasing the strength of the intramolecular hydrogen bond[6] also in Schiff bases.[7] With the help of *ab initio* calculations it was shown that the dipole moment of the proton transferred form is considerably reduced in comparison to systems with localized charge distribution like in Mannich bases.[8] It decreases the energy of the proton transfer state and makes the potential for the proton movement more shallow. The ν_s(OH) band shifts to lower frequencies; however, in contradiction to this, the intensity of the ν_s(OH) band decreases.

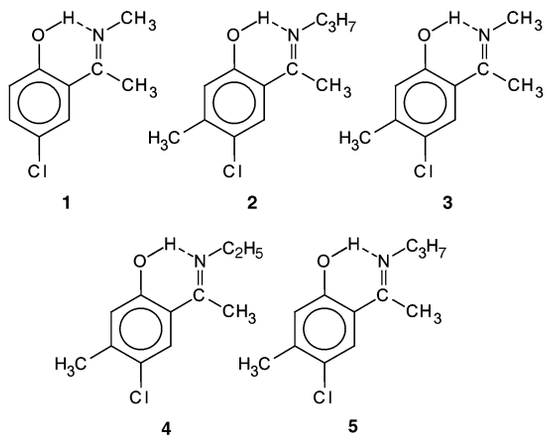
Further studies show that there exists another very effective way to modulate the potential for the proton transfer in Schiff bases.[9] It is the substitution of the alkyl or aryl group into the C–C(H)=N– moiety. That imposes an external (with respect to the chelate ring) squeezing of the hydrogen bond, efficiently reducing the O–H ··· N distance and changing the spectroscopic behaviour to that which becomes characteristic for very strong hydrogen bonds,[9–12] despite the opposite electronic influence of the alkyl and aryl substituents. This "steric" substitution moves the group of studied compounds to the "inversion" region, characteristic of LBHBs. Even small changes in the structure result in a strong modification of the proton distribution in such hydrogen bonds.

Among earlier studied compounds, the shortest OHN hydrogen bond (2.459 Å) known in the literature was discovered in 2-(*N*-alkyl-α-iminoethyl)phenol,[9] close to a linear OHN hydrogen bond, theoretically expected to be the shortest possible one (2.458 Å).[13] Strong delocalization can be concluded on the basis of O ··· H and H ··· N distances found equal to 1.20(4) and 1.32(3) Å or 1.15(4) and 1.38(2) Å for two different molecules in the crystal unit cell of this compound. Nevertheless, the proton is not located at the center of the hydrogen bridge (*cf.* also[13]).

The aim of this work is further modification of the hydrogen bond properties in the group of methyl substituted (in the –C(H)=N– unit) Schiff bases. It is performed by slight modification of the acid–base properties of the system by changing the substituents in the phenol ring as well as the length of the *N*-alkyl chain. It is also interesting to find out if it is possible to obtain a "symmetric" hydrogen bond with a single minimum potential for the proton movement in Schiff bases. All compounds studied here are derivatives of *p*-chlorophenol (see Scheme 2).

In compound **1**, substitution of the chlorine atom should move the proton in the direction of the nitrogen atom in comparison to 2-(*N*-alkyl-α-iminoethyl)phenol[9] (*cf.* the above mentioned O–H and H ··· N distances). Replacement of the N–CH_3 group by N–*n*-C_3H_7 in **2** should increase the tendency for the proton transfer. The methyl substitution in the phenol ring in **3**, **4** and **5** decreases the acidic properties of phenol in comparison to **1** and **2** and it should moderate the above-mentioned tendencies. Gradual replacement of the N–CH_3 group in **3** by the N–C_2H_5 group in **4** and by the N–*n*-C_3H_7

DOI: 10.1039/b106145n



Scheme 2

group in **5** should enhance the tendency for the proton transfer due to the increasing electron-donor function of the N-chains.

Information on such short hydrogen bonds is really missing in attempts to correlate the O ··· H and H ··· N distances in the OHN hydrogen bridge. From this point of view very interesting data have been presented recently.[14,15] In the complex of pentachlorophenol with 4-methylpyridine the hydrogen atom, localized exactly in the centre of the hydrogen bond, was obtained at 90 K by a neutron diffraction experiment. The shortest OHN hydrogen bridge was obtained, however, at 20 K; the O ··· N distance, 2.506(2) Å, was longer than in all Schiff bases with steric hindrance studied in this work. In this work we have got a set of very short OHN hydrogen bonds at room temperature, modified by a delicate change of chemical structure of Schiff bases.

The obtained results demonstrate, however, that the differences between particular systems do not follow the above-presented predictions, drawn up on the basis of the general rules of the electronic influence of substituents. It is a subject of detailed discussion in this work.

Experimental

Synthesis of **1**–**5** from stoichiometric mixtures of the corresponding ketones and amines in methanol was performed according to Ref.[16] After recrystallization from methanol solid yellow products were obtained, which were studied by X-ray diffraction at room temperature (293(2) K). Details of the crystal data and refinement of the compounds studied are given in Table 1.† Unit cell parameters and orientation matrices were calculated using least-squares techniques. Intensities were collected using the KUMA KM4 and KUMA KM4-CCD diffractometers in the ω–2θ scan mode with graphite-monochromator CuKα and MoKα radiation, respectively. The intensities of three standard reflections, monitored after every 100 intensity scans, gave no evidence of crystal decay. The data were corrected for Lorentz and polarization effects. No absorption correction was applied.

The structures were solved by direct methods using SHELXS-86[17] and refined by full-matrix least-squares fit on all F^2 using SHELXL-93.[18] The positions of the hydrogen atoms were determined from the difference Fourier synthesis. Only the hydrogen atoms of the 5-methyl group in **2** were placed in the geometrically calculated positions with the isotropic thermal factors taken as 1.2 U_{eq} of the neighbouring heavier atoms. Several cycles of refinement of the coordinates and anisotropic thermal parameters for the non-hydrogen atoms were performed. The scattering factors of neutral atoms were taken from Ref.[19] Details of the data collection procedure and values of the processing parameters are shown in Table 1.

ORTEPII views[20] of the molecules with thermal ellipsoids at 50% probability are shown in Figs. 1–5.

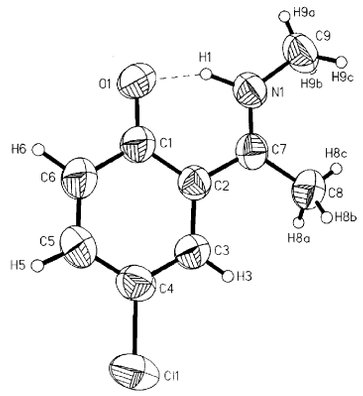


Fig. 1 Molecular structure and atom labelling system of 2-(*N*-methyl-α-iminoethyl)-4-chlorophenol **1**.

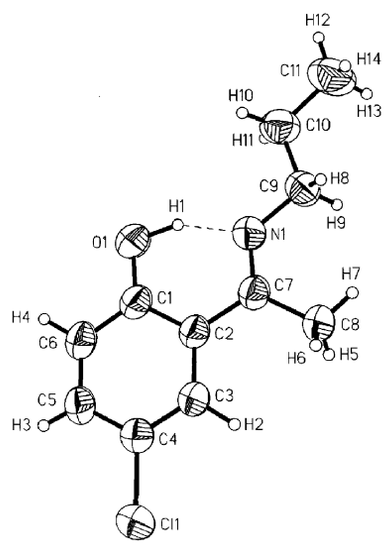


Fig. 2 Molecular structure and atom labelling system of 2-(*N*-propyl-α-iminoethyl)-4-chlorophenol **2**.

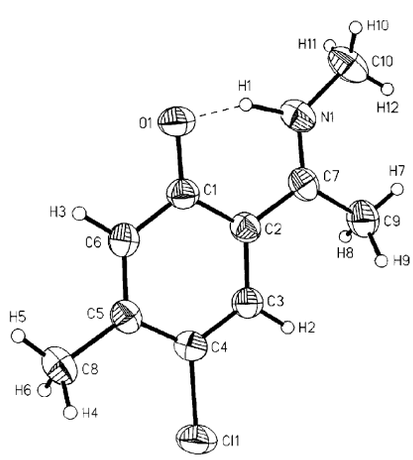


Fig. 3 Molecular structure and atom labelling system of 2-(*N*-methyl-α-iminoethyl)-4-chloro-5-methylphenol **3**.

Vibrational spectra were measured on an FT-IR Avatar 360 spectrophotometer, at a resolution of 1 cm^{-1}, in CCl_4 solutions, in cells with KBr windows.

† CCDC reference numbers 168009–168012 and 180650. See http://www.rsc.org/suppdata/p2/b1/b106145n/ for crystallographic files in .cif or other electronic format.

Table 1 Summary of data collection and processing parameters

Compound	**1**	**2**	**3**	**4**	**5**
Formula	$C_9H_{10}ClNO$	$C_{11}H_{14}ClNO$	$C_{10}H_{12}ClNO$	$C_{11}H_{14}ClNO$	$C_{12}H_{16}ClNO$
*M*r	183.63	211.68	197.66	211.68	225.71
Space group	$P\bar{1}$	$P\bar{1}$	$P2_1/n$	$P\bar{1}$	$P2_1/n$
Temperature/K	293(2)	293(2)	293(2)	293(2)	293(2)
Cell constants	25 ref., 25.5 < 2θ < 46.3	25 ref., 26.8 < 2θ < 48.7	25 ref., 24.2 < 2θ < 47.6	25 ref., 24.8 < 2θ < 48.7	
Crystal system	Triclinic	Triclinic	Monoclinic	Triclinic	Monoclinic
a/Å	6.411(2)	6.953(2)	4.867(10)	6.984(2)	12.421(2)
b/Å	7.273(2)	7.594(2)	12.082(2)	7.515(2)	7.185(1)
c/Å	10.251(3)	11.013(3)	16.367(3)	11.298(3)	25.571(3)
α/°	99.03(3)	79.12(3)		75.26(3)	
β/°	95.57(3)	83.75(3)	90.35(3)	79.65(3)	91.06(2)
γ/°	105.59(3)	76.06(3)		72.89(3)	
Cell volume/Å^3	449.8(1)	553.0(2)	962.4(3)	544.5(2)	2281.7(3)
Formula units/unit cell	2	2	4	2	8
D_{cal}/Mg m^{-3}	1.356	1.271	1.364	1.291	1.314
Max. crystal dimensions/mm	0.20 × 0.20 × 0.20	0.20 × 0.20 × 0.25	0.15 × 0.15 × 0.20	0.15 × 0.15 × 0.20	0.15 × 0.15 × 0.20
Scan width/°	Variable	Variable	Variable	Variable	Variable
No. of stand. ref. and int.	3 (100 ref.)	3 (100 ref.)	3 (100 ref.)	3 (100 ref.)	
Reflections measured	1841	2266	1993	2229	4457
2θ range/°	8.8–160.6	8.2–162.0	9.1–160.6	8.1–160.5	3.25–26.0
Range of *h*, *k*, *l*	−8/8, −8/8, −13/13	−8/8, −8/8, −14/14	0/5, 0/15, −20/20	−8/8, −9/9, −14/14	−15/15, −8/8, −21/31
Reflections observed [$F_o > 4\cdot\sigma(F_o)$]	1411	1942	1525	1911	3190
No. of parameters varied	150	184	167	184	399
GOF	1.059	1.060	1.026	1.034	1.147
$R_1 = \Sigma(\|F_o\| - \|F_c\|)/\Sigma(\|F_o\|)$	0.0456	0.0498	0.0463	0.0456	0.0486
$wR_2 = \{\Sigma[w(F_o^2 - F_o^2)^2]/\Sigma[w(F_o^2)^2]\}^{1/2}$	0.1295	0.1276	0.1196	0.1231	0.1143
Function minimized			$\Sigma\, w(\Delta F^2)^2$		
Largest feature final diff. map/e A^{-3}	0.245 and −0.238	0.456 and −0.320	0.267 and −0.324	0.270 and −0.380	0.247 and −0.308

$a_w = 1/[\sigma^2(F_o^2) + (a\cdot P)^2 + b\cdot P]$ where $P = [f\cdot$Max. of (0 or F_o^2) + (1 − f) × F_c^2].

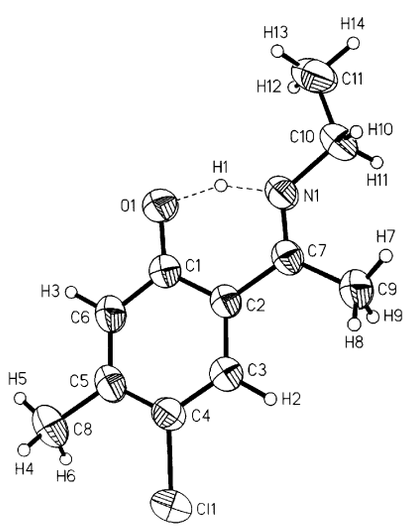


Fig. 4 Molecular structure and atom labelling system of 2-(*N*-ethyl-α-iminoethyl)-4-chloro-5-methylphenol **4**.

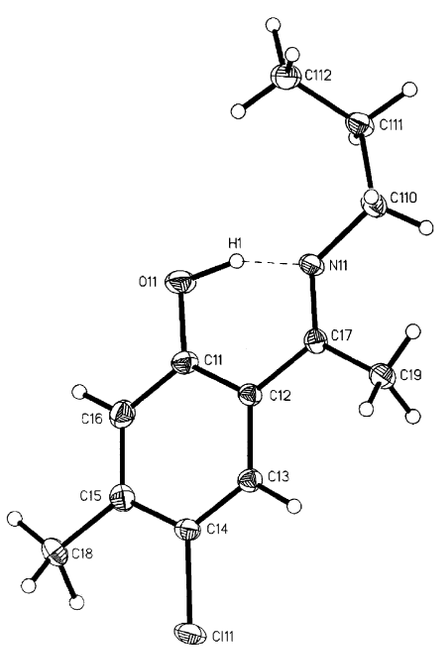


Fig. 5 Molecular structure and atom labelling system of 2-(*N*-propyl-α-iminoethyl)-4-chloro-5-methylphenol **5**.

Results and discussion

Molecular structures and the atom labelling system are shown in Figs. 1–5.

Molecular structure and steric interaction

In all the molecules (**1**–**5**) strong intramolecular hydrogen bonds are formed of very similar lengths from 2.487 Å in **2** and **3**, through 2.490 Å in **1**, 2.491 Å in **4** to 2.494(2) and 2.500(2) Å in two different molecules in the unit cell of **5** with similar O–H ··· N angles (155 ± 2°). These hydrogen bonds are pronouncedly shortened in comparison to *ortho*-hydroxy Schiff bases without steric interactions, where the O ··· N distances are longer than 2.51 Å (*cf.* Fig. 6).[9]

As in the previously studied Schiff bases[9–12] with alkyl- and phenyl-substituents in the –C(H)=N– group, the hydrogen bond shortening results from steric repulsion between those substituents and the phenol ring (see Scheme 3). The angles which are especially increased are marked in Scheme 3.

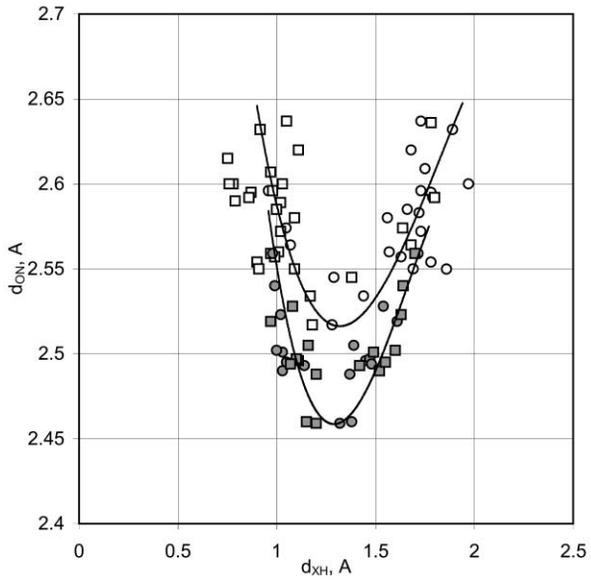
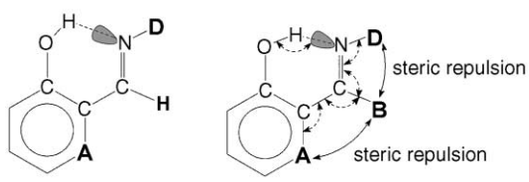


Fig. 6 Scatter plot in the (□) (d_{OH}, d_{ON}) and (○) (d_{HN}, d_{ON}) space for crystallographic data of Schiff bases.[21] Shaded symbols denote the results with steric substitution. The line drawing omits the points with d_{X-H} (where X = O, N) less than 0.96 Å.



Scheme 3

Introduction of a bulky **B** center instead of a hydrogen atom in the C(H)=N moiety makes the distances between atoms in **B** and **A**, **D** centers shorter by 0.4–0.6 Å than the sum of the van der Waals radii. It changes the valence angles and slightly increases the linearity of the hydrogen bridges (*cf.* Fig. 7). It

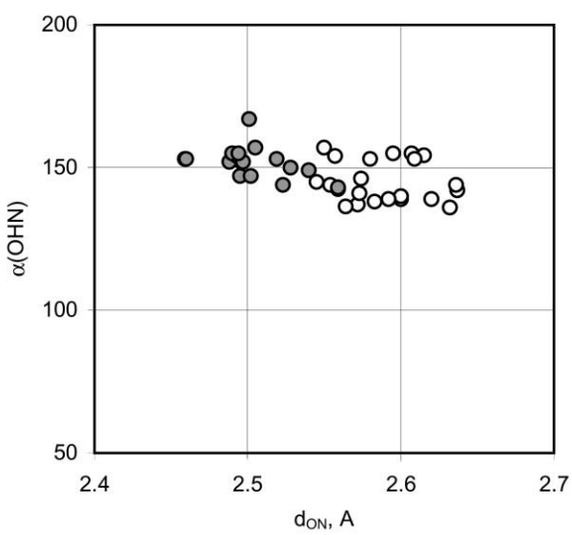


Fig. 7 Dependence of the OHN angle on d_{ON} distance for crystallographic data of Schiff bases.[21] Open circles—non sterically squeezed hydrogen bonds; shaded circles—compounds with steric interaction.

leads also to shortening of O ··· N distances and to strengthening of the hydrogen bonds. Scheme 4 presents a comparison of valence angles in five studied compounds (**1**–**5**) with representative molecules (molecular (**6**) and zwitterionic (**7**)) without the substituents in the –C(H)=N– moiety.[22] A real (on the order of 2.5°) increase of external angles of the chelate rings and consequent decrease of some internal angles can be mentioned.

Table 2 Energy[a] of steric repulsion between **A**, **B** and **D** fragments

Energy					
	Non bonded			Total	
	MM3	MM2	Deformation of angles	MM3	MM2
1	3.85	3.48	2.04	5.89	5.52
2	3.90	3.50	2.50	6.40	6.00
3	5.00	5.77	2.75	7.75	8.52
4	3.82	3.49	2.14	5.96	5.63
5	3.91	3.09	2.42	6.33	5.51
	3.96	2.81	2.42	6.38	5.23
6	1.99	2.29	—	1.99	2.29
7	1.40	1.39	—	1.40	1.39

[a] In kcal mol^{-1}.

A rough estimation of steric repulsion can be performed (Table 2) by calculation of the energy of non-bonded interactions between atoms in **A**, **B** and **D** centres, using the MM2 and MM3[23] potentials (Scheme 3) and energy of the valence angle deformations (discussed above) by applying the parameters given in reference 24.

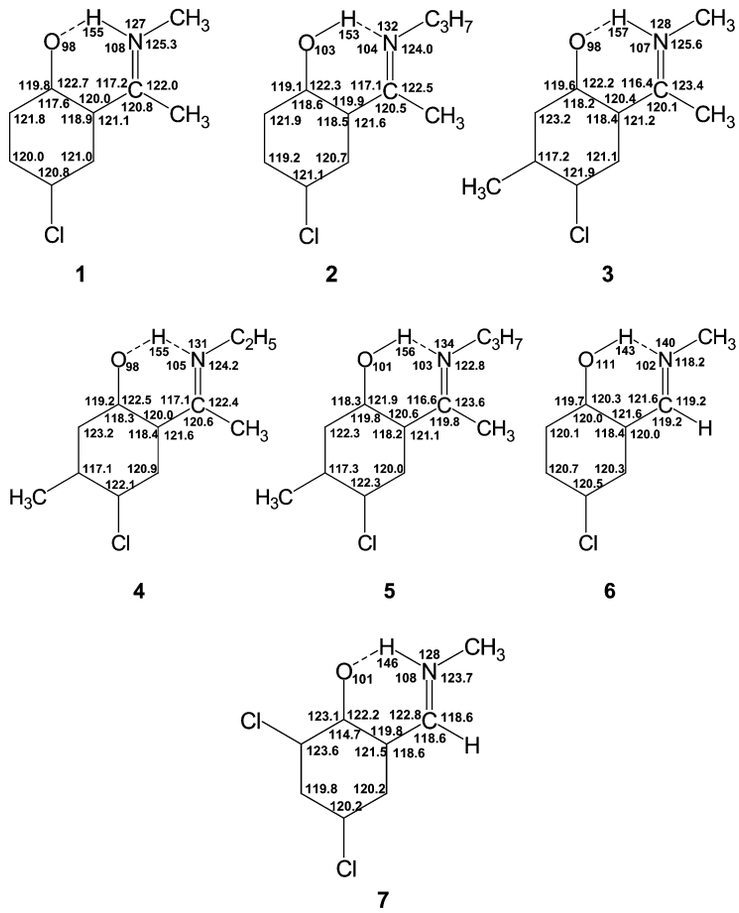
The increase of steric repulsion energy in compounds **1**–**5** by means of methyl group substitution can be estimated as ~ 5 kcal mol^{-1} in relation to compounds **6** or **7**, taken as reference states, as appropriate.

Hydrogen bond and proton localization

The structure of 2-(*N*-alkyl-α-iminoethyl)-4-chlorophenol (**1**) (see Fig. 1) can be compared with the structure of 2-(*N*-methyliminomethyl)-4-chlorophenol (**6**)—a compound without steric strengthening of intramolecular hydrogen bonding. Such a comparison demonstrates the very strong influence of the methyl substitution at the –C(H)=N–R moiety on the structure of **1**. It shortens the hydrogen bond from 2.559 to 2.490 Å and causes the proton transfer. The O ··· H distance becomes 1.52(4) Å and H ··· N, 1.03(3) Å, while related distances were 0.977 and 1.715 Å in **6**. The parameter $A = \Sigma_n(d_i - \bar{d}_i)^2/n \times 10^6$ characterizes the bond length differentiation resulting from the increase of the *ortho*-quinonoid character of the phenol ring.[25] In **1**, the parameter A is equal to 651 $Å^2$, which is close to the average between 942 and 325 $Å^2$ calculated for the ionic state of **7** and the molecular state of **6**, respectively.[22] Similarly, the calculated value of Q [$Q = (d_{CO} - d_{C7N}) + (d_{C2C7} - d_{C1C2})$] characterizing the resonance coupling of the chelate ring[6a–e] is equal to 0.048 Å, while it is −0.035 and 0.136 Å in **7** and **6**, respectively.[22] It allows the estimation of the content of the *ortho*-quinonoid resonance form in **1**, which is less than that for the ionic state in **7** and more than that for the molecular state in **6** (see Table 3). It suggests that hydrogen bonding in **1**, although ionic, is shifted in the direction of the strongest, **C** type (Scheme 1) hydrogen bonds, with increased delocalisation of the proton arising from a decrease of the barrier for the proton transfer. The O ··· H distance in **1** is much shorter than in **7**.

Serious strengthening of the hydrogen bond in 2-(*N*-methyl-α-iminoethyl)-4-chlorophenol is also evident from comparison of the IR spectra of this compound and 2-(*N*-methyliminomethyl)-4-chlorophenol (**6**) (*cf.* Fig. 8). A similar red shift of ν_s(OH) bands resulting from methyl substitution in **2**–**5** was observed. The same conclusions follow from the spectra of related compounds with *N*-benzyl substituents.[10]

In compounds **2** and **5** the molecular structure was found, despite the expectations based on the electronic influence of the N–*n*-C_3H_7 chain on the basicity of the nitrogen atom. The situation can be explained as a result of shielding of the hydrogen bond from the surroundings caused by the N–*n*-C_3H_7 chain in



Scheme 4

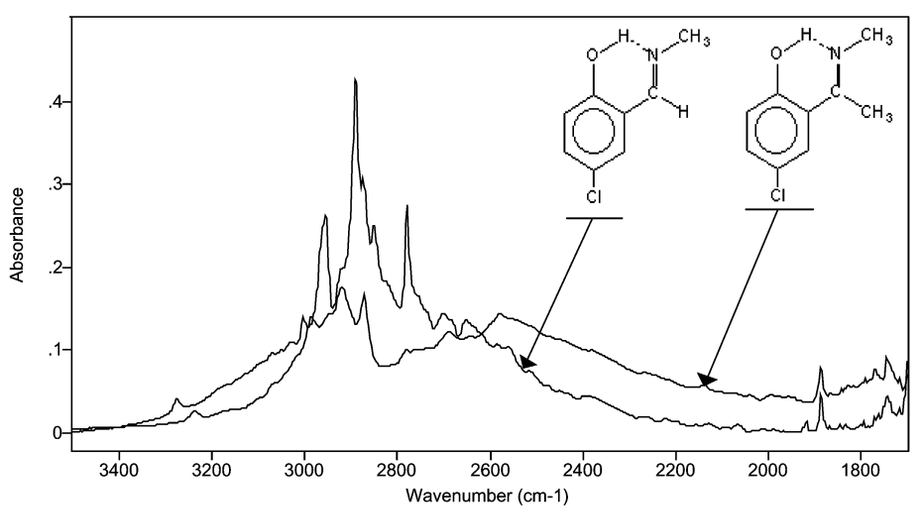


Fig. 8 Differences in IR spectra of two analogous Schiff bases resulting from the methyl group substitution.

the solid state. Such an effect was observed for the 2-(*N*,*N*-dialkylamino)methyl-4-nitrophenols[26] in the solid state, as well as for 2-(*N*,*N*-dialkylamino)methyl-4-nitro- and 2-(*N*,*N*-dialkylamino)methyl-3,4,6-trichlorophenols in methanol solutions.[27] In the first case, the *N*,*N*-dimethyl and *N*,*N*-diethyl derivatives were zwitterionic, while the *N*,*N*-diisopropyl derivative was molecular. In the second case, the amount of zwitterionic isomer in solution was decreased with the increasing length of N-chains, when substituents in the phenol ring were kept the same. The H ··· N distance appears to be much shorter in **2** than in **6**, however.

It makes the proton more delocalised in the OHN bridge and the barrier for the proton transfer decreases. The O ··· H and H ··· N distances equalization becomes even more effective in **3** and **4**. In **3** one observes the ionic state of the hydrogen bond, the O ··· N distance is a little bit shorter than in **1**, but the position of the proton is definitely nearer to the center of the hydrogen bridge. Introduction of a methyl substituent in position 5 of the phenol ring decreases the acidity of phenol (in comparison to **1**) and shifts the equilibrium back in the direction of a molecular state.

The values of the CO bond length for all the compounds are also included in Table 3. This bond length can serve as a crude measure of proton transfer in complexes of phenols.[28] In

Table 3 Hydrogen bond parameters and selected bond lengths (Å) and angles (°), with esd's in parentheses, in pseudoaromatic chelate rings

	Form of HB	*d*(OH)	*d*(ON)	*d*(HN)	*α*(OHN)	*d*(CO)	*d*(CN)	*A*	% of keto form	*Q*
1	O ··· H–N	1.52(4)	2.490(2)	1.03(3)	155(3)	1.300(2)	1.288(2)	651	35	0.048
2	O–H ··· N	1.02(4)	2.487(2)	1.53(4)	153(3)	1.317(2)	1.283(2)	462	32	0.067
3	O ··· H–N	1.43(4)	2.487(2)	1.11(4)	157(4)	1.312(2)	1.291(2)	348	34	0.055
4	O ··· H ··· N	1.33(4)	2.491(2)	1.22(4)	155(4)	1.316(2)	1.281(2)	250	30	0.082
5	O–H ··· N	1.05(4)	2.494(2)	1.50(4)	156(3)	1.345(3)	1.287(3)	208	25	0.118
	O–H ··· N	1.03(3)	2.500(2)	1.52(3)	156(3)	1.344(2)	1.297(3)	254	27	0.103
6	O–H ··· N	0.977	2.559	1.715	142.5	1.349(6)	1.269(6)	325	22	0.136
7	O ··· H–N	1.637	2.574	1.048	146.1	1.280(3)	1.291(3)	942	47	−0.035

phenols this distance is within the range 1.37–1.34 Å; it becomes 1.33–1.31 Å in the shortest hydrogen bonds with 50% of proton transfer and reaches 1.29–1.26 Å in phenolates. The analysis of the data of Table 3 shows that the parameter *A*, describing bond length differentiation in the phenol ring, grows with the decrease of the CO distance, so does the calculated percent of keto form. From this point of view sterically hindered Schiff bases follow the rules found for "ordinary" Schiff bases without steric strain.[22]

The best equalization of the O–H and H ··· N bond lengths was found in **4** (*cf.* Table 3), contrary to expectations that the extension of the N–CH_3 to the N–C_2H_5 chain should increase the basic abilities of the nitrogen atom. Steric shielding of the reaction center by the longer *N*-alkyl chain appears to be more effective than these electronic influences. This effect becomes even more pronounced in **5**. The more bulky N–*n*-C_3H_7 chain reinforces shielding from the surroundings to such an extent that hydrogen bonding becomes molecular (enol form). Acid and base centres in **2** and **5** appear in a less polar environment than in **3** and **4**. It demonstrates how important is the influence of the surroundings on the proton location in the studied molecules.

It is hard to make judgements about the localisation of the proton in **3** and **4** only on the basis of X-ray measurements. The obtained results should be accepted as evidence of strong proton delocalisation in these compounds. Additional support for this statement is provided by an independent determination (with CuKα radiation) of the structure of **4**, where the O ··· H and H ··· N distances were obtained opposite to those given in Table 3 (d_{OH} = 1.22 Å, d_{NH} = 1.30 Å).

Ab initio and DFT calculations of the potential for proton movement

In order to understand the influence of "steric" substitution on the intramolecular hydrogen bond in Schiff bases, "single point" calculations of the adiabatic potential for the proton movement were performed for two model compounds: 2-(*N*-methyliminomethyl)phenol, for which the molecular structure was not determined experimentally as it is a liquid, and its analogue, 2-(*N*-methyl-α-iminoethyl)phenol with the methyl group substituted in the C(H)=N–CH_3 fragment. The calculations were performed at MP2/6-31G**[29,30] and DFT/6-31G**[30,31] levels using the Gaussian 94 program.[32]

Fig. 9 shows the energy profile for proton movement within the hydrogen bridge for both of these compounds. The effect of shortening of the hydrogen bond upon the methyl group substitution appears to be very clear from the potentials' comparison.

Very similar modifications of the potential were found by means of two quantum mechanical methods (DFT and MP2). The calculations were performed by extension of the OH bond length, while positions of all the other atoms were frozen at the equilibrium positions, optimized for each applied method. Such an approach seems to be rational when one makes an attempt to obtain the potential for the fast movement of proton, at least in the solid state.

On the other hand, in bent hydrogen bonds one can also expect some deviation of the proton movement from the OH direction. The second variant of the calculations was applied, where the COH and CCOH angles were allowed to be freely modified in the course of O–H bond extension. The modification of the potentials is presented in Figs. 10A, 10B. From the figures it is obvious that the "softer" model gives a more flat potential for the proton movement. Barriers for the proton transfer decrease, and the proton becomes more labile.

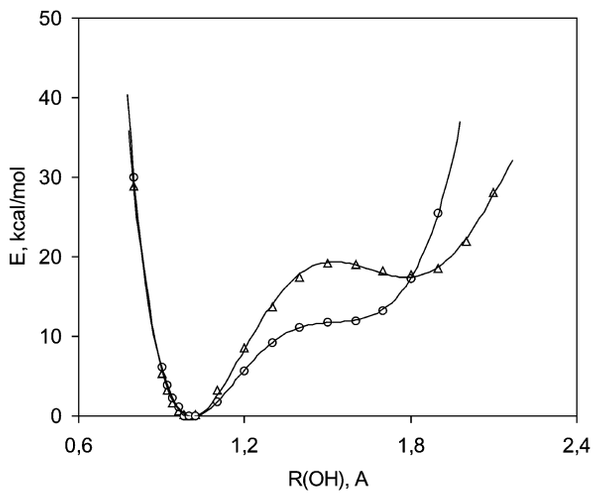


Fig. 9 Adiabatic potential for the proton movement for 2-(*N*-methyl-α-iminoethyl)phenol (○) and 2-(*N*-methyliminomethyl)phenol (Δ) at the B3LYP/6-31G(d,p) level.

All the approaches used evidently support the idea that the steric repulsion of the substituted methyl group decreases the energy of the minimum for the $O^- \cdots H–N^+$ state and makes the potential more shallow. The barrier for such a flat potential reduces in agreement with the experimental observations.

Moreover, the calculations were performed in the gas phase and one can expect an even stronger decrease of energy of the minimum for the $O^- \cdots H–N^+$ state and more advanced delocalisation of proton.

The potentials discussed above describe the dynamics of proton movement. Predicted due to widening of the potential at the minimum, the red shift of IR absorption comes in full agreement with the experiment. Discussion of the proton position in stationary states, studied by X-ray crystallography, needs calculations with full optimisation of all structural parameters. It allows the establishment of the energy difference between two tautomeric states. Such calculations were performed with full optimisation of the enol and proton transfer states. The increase of the energy related to the proton transfer in 2-(*N*-methyliminomethyl)phenol is equal to 5 kcal mol^{-1} and decreases to 2.77 kcal mol^{-1} in 2-(*N*-methyl-α-iminoethyl)-phenol. Analogous values were obtained for related *N*-benzyl derivatives (4.87 and 2.76 kcal mol^{-1}, respectively).[9] The significant decrease of the energy of the proton transfer process (ΔE_{PT}) in such calculations (Figs. 9 and 10) can be estimated as 2.75 kcal mol^{-1}. Therefore, the proton transfer state is easily accessible in sterically hindered Schiff bases, especially if taking into account that calculations were performed for the gas phase.

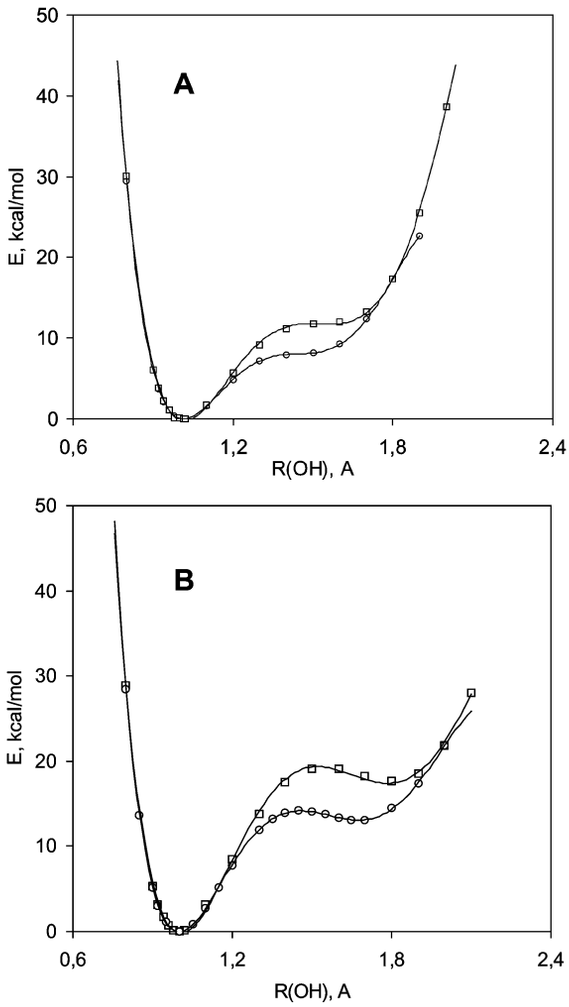


Fig. 10 (A) Comparison of the adiabatic potential for the proton movement for 2-(*N*-methyl-α-iminoethyl)phenol at B3LYP/6-31G(d,p) level: (□) obtained by the OH length modulation, other parameters fixed; (○) obtained by the OH length and COH and CCOH angles optimization, other parameters fixed. (B) Comparison of the adiabatic potential for the proton movement for 2-(*N*-methyliminomethyl)phenol at B3LYP/6-31G(d,p) level: (□) obtained by the OH length modulation, other parameters fixed; (○) obtained by the OH length and COH and CCOH angles optimization, other parameters fixed.

Conclusions

A new class of sterically modified hydrogen bonds in Schiff bases has been discovered. Introducing an alkyl or aryl substituent into the C(H)=N–CH_3 moiety leads to substantial shortening of the hydrogen bond length and a change of the spectroscopic behaviour of such systems.

Especially interesting are the systems from the intermediate (critical) region, where the low barrier for the proton transfer within hydrogen bonds can be anticipated. Five compounds (**1**–**5**) were synthesised and their crystal structures were determined. All these compounds, derivatives of *p*-chlorophenol, really contain very short OHN hydrogen bonds (equal to or less than 2.500 Å) and belong to the group of critical hydrogen bonds. Changing the substituents at the phenol ring or an extension of the N-chain makes possible modification of the potential for proton transfer.

Addition of a methyl substituent at position 5 of the phenol ring in **1** shifts the equilibrium in the direction of enol type hydrogen bonds, but the hydrogen bond persists in being zwitterionic (in **3**). Such a combination of substituent effects (5-methyl-4-chloro substitution) gives more intermediate proton positions—d_{OH} = 1.43 Å and d_{NH} = 1.11 Å. Delicate extension of the N-chain, from N–CH_3 to N–C_2H_5 when going from **3** to **4**, causes a further shift of the equilibrium in the direction of an enol type hydrogen bridge (in **4**). The apparent proton position appears labile to such an extent that two slight technical differences in the X-ray determinations gave two opposite solutions, one with 1.33 and 1.22 Å OH and HN bond lengths distribution, the second with inversed bond length ordering. The positions of all other atoms were practically the same in both solved structures.

This can be accepted as evidence of a large proton delocalization within the hydrogen bond, characteristic of the very low potential barrier for the proton transfer.

Further extension of the N-chain to a propyl group shifts the structure to a typically enol form (in **5**).

It was shown that steric repulsion and slight modification of substituents can give the possibility of drastic modification of the potential shape for the proton transfer and reduction of the barrier in *ortho*-hydroxy Schiff bases, which opens the way for practical application of these compounds. Such a situation is caused by the fact that compounds **1**–**5** belong (due to steric squeezing of the hydrogen bridges) to the range of intermediate (or inversion) hydrogen bridges.

The N ··· O distances in **1**–**5** look very much alike, which suggests that the hydrogen bridge shortening mainly results from steric interactions.

Acknowledgements

The authors acknowledge the financial support of KBN grant N 3 T09A 037 16 and WCSS center for computing facilities.

References

1 (*a*) A. S. Mildvan, T. K. Harris and C. Abeygunawardana, *Methods Enzymol.*, 1999, **308**, 219; (*b*) W. W. Cleland, *Arch. Biochem. Biophys.*, 2000, **382**, 1; (*c*) W. W. Cleland and M. M. Kreevoy, *Science*, 1995, **269**, 104; (*d*) A. Warshel, A. Papazyan and P. Kollman, *Science*, 1995, **269**, 102; (*e*) S. Shan, S. Loh and D. Herschlag, *Science*, 1996, **272**, 97; (*f*) G. Zundel, *Proton Polarizability of Hydrogen Bonds and Proton Transfer Processes, Their Role in Electrochemistry and Biology*, G. Zundel, Munchen-Salzburg, 1997; (*g*) E. L. Ash, J. Sudmeier, E. C. De Fabo and W. Bachovchin, *Science*, 1997, **278**, 1128.
2 M. Cuma, S. Scheiner and T. Kar, *J. Mol. Struct. (THEOCHEM)*, 1999, **467**, 37.
3 S. Scheiner, *Acc. Chem. Res.*, 1994, **27**, 402.
4 W. W. Cleland and M. M. Kreevoy, *Science*, 1994, **264**, 1887.
5 P. A. Frey, S. A. Whitt and J. B. Tobin, *Science*, 1994, **264**, 1927.
6 (*a*) G. Gilli, F. Bellucci, V. Ferretti and V. Bertolasi, *J. Am. Chem. Soc.*, 1989, **111**, 1023; (*b*) P. Gilli, V. Bertolasi, V. Ferretti and G. Gilli, *J. Am. Chem. Soc.*, 1994, **116**, 909; (*c*) V. Bertolasi, P. Gilli, V. Ferretti and G. Gilli, *Acta Crystallogr., Sect. B*, 1995, **51**, 1004; (*d*) P. Gilli, V. Ferretti, V. Bertolasi and G. Gilli, in M. Hargittai and I. Hargittai (Eds.), *Advances in Molecular Structure Research*, JAI Press, Greenwich, CT, 1996, Vol. 2, p. 667; (*e*) V. Bertolasi, P. Gilli, V. Ferretti and G. Gilli, *J. Am. Chem. Soc.*, 2000, **122**, 10405; (*f*) B. Schiott, B. B. Iversen, G. K. H. Madsen and T. C. Bruice, *J. Am. Chem. Soc.*, 1998, **120**, 12117; (*g*) G. K. H. Madsen, B. B. Iversen, F. K. Larsen, M. Kapon, G. M. Reisener and F. H. Herbstein, *J. Am. Chem. Soc.*, 1998, **120**, 10040.
7 A. Filarowski and A. Koll, *Vib. Spectrosc.*, 1998, **17**, 123.
8 A. Filarowski, PhD Thesis, Wroclaw, 1996.
9 A. Filarowski, T. Glowiak and A. Koll, *J. Mol. Struct.*, 1999, **484**, 75.
10 A. Filarowski, A. Koll and T. Glowiak, *Monatsh. Chem.*, 1999, **130**, 1097.
11 A. Mandal, A. Filarowski, T. Glowiak, A. Koll and S. Mukherjee, *J. Mol. Struct. (THEOCHEM)*, 2002, **577**, 153.
12 A. Filarowski, A. Koll and T. Glowiak, *J. Mol. Struct.*, 2002, in the press.
13 T. Steiner, *J. Phys. Chem. A*, 1998, **102**, 7041.
14 T. Steiner, *Angew. Chem., Int. Ed.*, 2002, **41**, 48.
15 T. Steiner, I. Majerz and C. C. Wilson, *Angew. Chem., Int. Ed.*, 2001, **40**, 2651.
16 *Vogel's Textbook of Practical Organic Chemistry*, B. S. Furnuss, A. J. Hannaford, P. W. G. Smith and A. Tatchell, Longmans, New York, 1989, pp. 997–999.

17 G. M. Sheldrick, *Acta Crystallogr., Sect. A*, 1990, **46**, 467.
18 SHELXL 93. Crystal structure Refinement, Department of Inorganic Chemistry, University of Göttingen, Germany.
19 *International Tables for X-ray Crystallography*, Kynoch Press, Birmingham, UK, 1974, vol. 4.
20 C. K. Johnson, *ORTEPII Report ORNL-5138*, Oak Ridge National Laboratory, Tennessee, USA, 1976.
21 Cambridge Structural Database (CSD: F. H. Allen and O. Kennard, *Chem. Des. Autom. News*, 1993, **8**, 1) update 5.20 (Oct. 2000).
22 A. Filarowski, A. Koll, T. Glowiak, E. Majewski and T. Dziembowska, *Ber. Bunsenges. Phys. Chem.*, 1998, **102**, 393.
23 J.-H. Lii and N. L. Allinger, *J. Am. Chem. Soc.*, 1989, **111**, 8576.
24 A. I. Kitaygorodsky, *Molecular Crystals and Molecules*, Academic Press, New York, 1973.
25 (*a*) A. Julg and P. Francois, *Theor. Chim. Acta*, 1967, **7**, 249; (*b*) A. Julg, in E. D. Bregmann and B. Pullman (Eds.), *Aromaticity, Pseudoaromaticity and Antiaromaticity*, Academic Press, New York, 1971, pp 383–385; (*c*) J. Kruszewski and T. M. Krygowski, *Tetrahedron Lett.*, 1972, **36**, 3839.
26 A. Koll and P. Wolschann, *Monatsh. Chem.*, 1996, **127**, 475.
27 M. Rospenk, *J. Mol. Struct.*, 1990, **221**, 109.
28 I. Majerz, Z. Malarski and L. Sobczyk, *Chem. Phys. Lett.*, 1997, **274**, 361.
29 (*a*) C. Moller and M. S. Plesset, *Phys. Rev.*, 1934, **46**, 618; (*b*) J. A. Pople, J. S. Binkley and R. Seeger, *Int. J. Quantum Chem., Symp.*, 1976, **10**, 1; (*c*) R. Krishnan and J. A. Pople, *Int. J. Quantum Chem., Symp.*, 1976, **14**, 91.
30 (*a*) W. J. Hehre, R. Ditchfield and J. A. Pople, *J. Chem. Phys.*, 1972, **56**, 2257; (*b*) P. C. Hariharan and J. A. Pople, *Theor. Chim. Acta*, 1973, **28**, 213; (*c*) M. M. Francl, W. J. Pietro, W. J. Hehre, J. S. Binkley, M. S. Gordon and J. A. Pople, *Int. J. Chem. Phys.*, 1982, **77**, 3654.
31 (*a*) A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 5648; (*b*) C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B*, 1993, **37**, 785.
32 Gaussian 94, M. J. Frisch, G. W. Trucks, H. B. Schlegel, P. M. W. Gill, B. G. Johnson, M. A. Robb, J. R. Cheeseman T. Keith, G. A. Petersson, J. A. Montgomery, K. Raghavachari, M. A. Al-Laham, V. G. Zakrzewski, J. V. Ortiz, J. B. Foresman, J. Cioslowski, B. B. Stefanov, A. Nanayakkara, M. Challacombe, C. Y. Peng, Y. Ayala, W. Chen, M. W. Wong, J. L. Andres, E. S. Replogle, R. Gomperts, R. L. Martin, D. J. Fox, J. S. Binkley, D. J. Defrees, J. Baker, J. P. Stewart, M. Head-Gordon, C. Gonzalez and J. A. Pople, Gaussian, Inc., Pittsburgh, PA, 1995.