

Solid-state structure of 1,2-dimethoxybenzene (veratrole) and related methoxybenzenes. X-Ray crystallography and ^{13}C nuclear magnetic resonance tensor analysis



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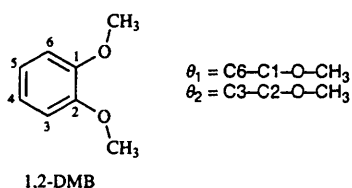
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We present here the single crystal X-ray structure of 1,2-dimethoxybenzene which reveals the methoxy groups to be *trans* and twisted out of the plane by -5.0 and 8.6° . Using variable spinning rate ^{13}C CP MAS NMR spectroscopy, the principal shielding tensors were measured for anisole, 1,2-dimethoxybenzene, 1,4-dimethoxybenzene and 1,3,5-trimethoxybenzene. From this work the principal elements were obtained for static benzene ($\sigma_{11} = 222$, $\sigma_{22} = 147$ and $\sigma_{33} = 14$) and for the substituent chemical shift of a planar methoxy group. The *ab initio* tensors of 1,2-dimethoxybenzene were calculated by the GIAO and LORG methods using the X-ray data as input. The CP MAS spectrum of 1,3-dimethoxybenzene reveals that this molecule adopts the asymmetric planar conformation.

Introduction

The conformational preferences of 1,2-dimethoxybenzene (1,2-DMB)[†] has been a subject of much controversy over the years. This moiety is common in natural products where there exists an established relationship between bioactivity and conformation.^{1,2} In cyclohomologues the relative orientation of the oxygens can affect the susceptibility of the benzene ring towards electrophilic substitution.³ In the present paper, the X-ray structure and the ^{13}C NMR tensor measurements of 1,2-DMB are presented and together give a clearer understanding of the electronic properties in this material.

In the gas phase, photoelectron spectroscopic data for 1,2-DMB have been interpreted in terms of a non-planar ($\theta_1 = 0^\circ$, $\theta_2 = 90^\circ$) conformation.²



In solution the problem still remains controversial; partition coefficients,² temperature dependence of the dipole moment,⁴ dielectric relaxation times,⁵ the non-linear dielectric effect parameter⁶ and ^{17}O NMR spectroscopy⁷ all require a non-planar conformation for 1,2-DMB. In contrast, however, ^{13}C NMR shifts, spin-lattice relaxation times⁸ and long-range ^1H - ^1H coupling constants agree with the existence of 1,2-DMB as a planar conformer. From the average $^5J_{\text{H,CH}_3} = -0.14$ Hz, the *trans*-coplanar conformer ($\theta_1 = \theta_2 = 0^\circ$) was shown to be predominant with some torsional motions as large as 20° . The planarity of 1,2-DMB was attributed to solvation effects which

can overcome the energy barrier between planar and non-planar conformers.⁹

In the solid state, the structure of 1,2-DMB has been characterized to be a mixture of planar and non-planar conformers based on multiplicities found in the low frequency methyl torsion transitions in the Raman spectrum at 130 K.¹⁰ This is in contrast to an X-ray literature survey where 1,2-DMB derivatives (non-3-substituted) prefer planar arrangements.^{2,11} The results of the computation of the crystal lattice energies for some of these derivatives suggest non-planar conformations are favoured *in vacuo*, but due to crystal packing, the planar conformations prevail.¹² The X-ray structure of 1,2-DMB·Cr(CO)₃ shows the *trans*-coplanar 1,2-DMB molecule to possess an effective C_2 symmetry with one methyl group situated slightly above the aromatic plane by 0.06 \AA .¹³

Solid-state anisole (MB) has also been investigated using low frequency Raman spectroscopy at 130 K.¹⁴ It was postulated that MB is likely to exist as two different conformers as evidenced by the splitting into a doublet of the methyl torsional band of the deuteriated analogues. In a recent publication, the ^{13}C tensors of MB were evaluated from the simulated 2D MAT spectrum at 205 K and found to be in agreement with *ab initio* calculations based on an optimized planar structure. Also a shoulder on the methoxy resonance in the CP MAS spectrum at 180 K was attributed to crystal packing effects.¹⁵

Theoretical investigations into the conformational preferences of MB and the dimethoxybenzenes are restricted by the lack of X-ray data which serve as reference geometries. These compounds have low melting points: MB (mp = -37.5°C), 1,2-DMB (mp = 15°C) and 1,3-DMB (mp = -52°C) with the exception of 1,4-DMB (mp = 59°C).¹⁶ Molecular mechanics (MM) studies have indicated that it is difficult to describe the $\text{C}_{\text{sp}2}\text{-C}_{\text{sp}2}\text{-O-C}_{\text{sp}3}$ torsion because reliable force field parameters are unavailable¹⁷ and the hybridization state of the oxygen remains independent of dihedral angle. MM calculations on 1,2-DMB suggest it can exist in any or all of four conformers: (0° , 0°), (0° , 90°), (0° , 180°), (90° , 270°).¹⁸ Recent *ab initio* molecular orbital calculations on 1,2-DMB at the STO-3G

[†] MB, DMB and TMB refer to monomethoxy-, dimethoxy- and trimethoxy-benzene.

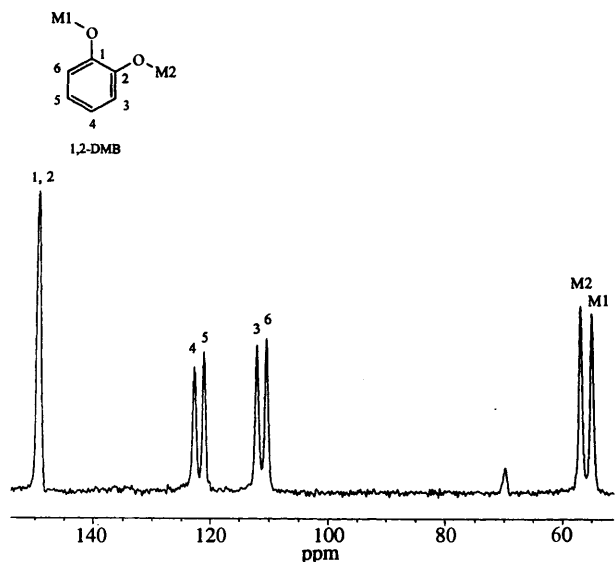


Fig. 1 50.32 MHz ^{13}C CP MAS NMR spectrum of 1,2-DMB at 260 K

level¹⁹ indicate that the (0° , 0°) conformation is stabilized by 0.5 kcal mol⁻¹ relative to the perpendicular one (0° , 90°).

Relating isotropic ^{13}C NMR chemical shifts to electronic structure^{20,21} is more straightforward in the solid state than in solution where conformational averaging is eliminated. However caution must be exercised since multiplicities can also originate from the presence of more than one molecule in the crystallographic unit cell²² or quadrupolar nuclei.²³ With the X-ray structures in hand, much work in this area has been performed on 1,2-dialkoxybenz-annulated crown ethers.^{24,25}

Previous work in these laboratories revealed seven lines in the low temperature ^{13}C CP MAS powder spectrum of 1,2-DMB (Fig. 1),²⁶ the origin of which can be attributed to (i) a single conformer with approximate C_2 symmetry²⁷ or (ii) two conformers each with C_2 symmetry. Accordingly, a single crystal X-ray structure of 1,2-DMB was required to resolve this problem.

To complement the solid-state structure obtained by X-ray and CP MAS, a shielding tensor analysis was undertaken. The electronic shielding of a nucleus is dependent on the molecular orientation relative to the external magnetic field and is described by the shielding tensor which has three mutually orthogonal principal elements, $\sigma_{11} > \sigma_{22} > \sigma_{33}$.²⁸⁻³¹ σ_{11} and σ_{22} are mainly π shielding, the former in the direction of the $\text{C}_{\text{ar}}-\text{H}$ and $\text{C}_{\text{ar}}-\text{O}$ bonds while σ_{33} is mainly σ shielding in a direction perpendicular to the benzene plane.³² If the spinning frequency is reduced relative to the chemical shift anisotropy then the isotropic line in the CP MAS spectrum is flanked on both sides by sidebands spaced at the spinning frequency. The intensities of the spinning sidebands are related to the chemical shift anisotropy and provide an opportunity to recover the shift parameters. The Herzfeld and Berger method³³ is a graphical mathematical resolution for this technique and is used herein to obtain the shielding tensors for MB, 1,2-DMB, 1,4-DMB and 1,3,5-TMB.

A potential drawback in relating these tensors to the 3D electronic structure is that the parent molecule benzene undergoes a rapid in-plane motion at experimentally accessible temperatures thereby averaging σ_{11} and σ_{22} . However from our data it proved possible to directly calculate the tensors of static benzene.³⁴⁻³⁶ From this, the anisotropic substituent chemical shifts (SCS) of a planar methoxy group were assessed in order to study the 3D electronic properties of these compounds, particularly 1,2-DMB. In addition *ab initio* shielding tensor calculations on 1,2-DMB using the GIAO (gauge invariant atomic orbital)³⁷ and LORG (localized orbital—local origin)³⁸ methods were performed.

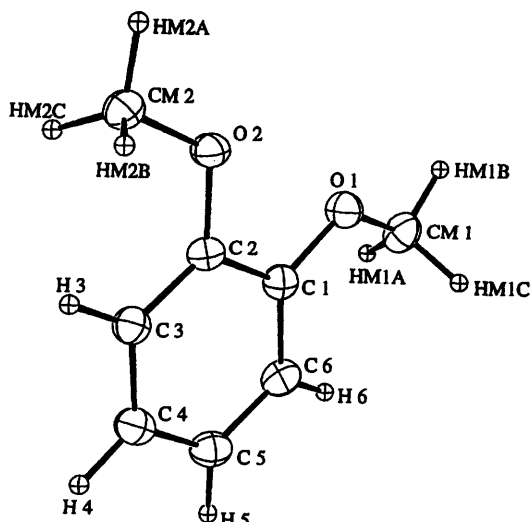


Fig. 2 ORTEP plot of 1,2-DMB at 150 K

Results and discussion

X-Ray structure of 1,2-DMB

The ORTEP diagram (Fig. 2) shows the methoxy groups are twisted on the same side out of the aromatic plane $\text{C6}-\text{C1}-\text{O1}-\text{CM1} = 8.6^\circ$ and $\text{C3}-\text{C2}-\text{O2}-\text{CM2} = -5.0^\circ$.[†] The near coplanarity of the methoxy groups permits good overlap of the oxygen p-type lone pairs with *ipso* p-orbitals.³⁹ Although the methyl groups in *ortho*-dimethoxy compounds (non-3-substituted) are usually displaced on opposite sides of the ring, the present situation is not unique.⁴⁰

The $\text{C}_{\text{ar}}-\text{O}$ vectors are bent towards each other presumably to reduce the steric repulsion between the methyl protons and *ortho*-aromatic protons⁴¹ where $\text{C6}-\text{C1}-\text{O1}$ and $\text{C3}-\text{C2}-\text{O2}$ are *ca.* 124.5° .[§] In contrast methyl vinyl ether has been shown to exist in the more sterically congested *syn*-planar conformation, based on vibrational spectroscopy,⁴² electron diffraction studies⁴³ and *ab initio* calculations. Theoretical calculations on methyl vinyl ether and related heteroanalogues show the *syn*-planar conformation has the lowest overall molecular dipole moment. The calculated⁴⁴ and experimental⁴⁵ *syn/anti* energy difference was found to be 2.82 and 1.26 kcal mol⁻¹, respectively.

In the packing diagram, looking down the *c* axis, roughly coplanar (23°) 1,2-DMB units are arranged in a mutually perpendicular fashion (Fig. 3). The closest $\text{X} \cdots \text{H}$ intermolecular contacts (Fig. 4) are all within the appropriate van der Waals radii (Table 1). The perpendicular molecules undergo mutual contacts $\text{C3} \cdots \text{H3}$ involving the same side of the aromatic plane. The other perpendicular contacts involve $\text{O1} \cdots \text{HM2C}$ and $\text{O2} \cdots \text{HM1B}$. There are also $\text{O2} \cdots \text{H5}$ and $\text{O1} \cdots \text{H5}$ contacts between parallel molecules.

^{13}C Assignments of 1,2-DMB

Solid-state assignments were facilitated by the synthesis of *ortho*-[^2H]1,2-DMB.⁴⁶ In the CP/MAS dipolar dephased spectrum of this compound [Fig. 5(b)] there are two resonances within 1.0 ppm of the *ortho* site solution value (Table 2) at half the intensity of the *ipso* and methyl peaks. Clearly the reson-

[†] Atomic co-ordinates, thermal parameters and bond lengths and angles have been deposited at the Cambridge Crystallographic Data Centre (CCDC). See 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1996, Issue 1. Any request to the CCDC should quote the full literature citation and the reference number 188/40.

[§] In non-planar conformations the $\text{C}-\text{C}-\text{O}$ bond angles are significantly smaller $119.5 \pm 0.7^\circ$.²

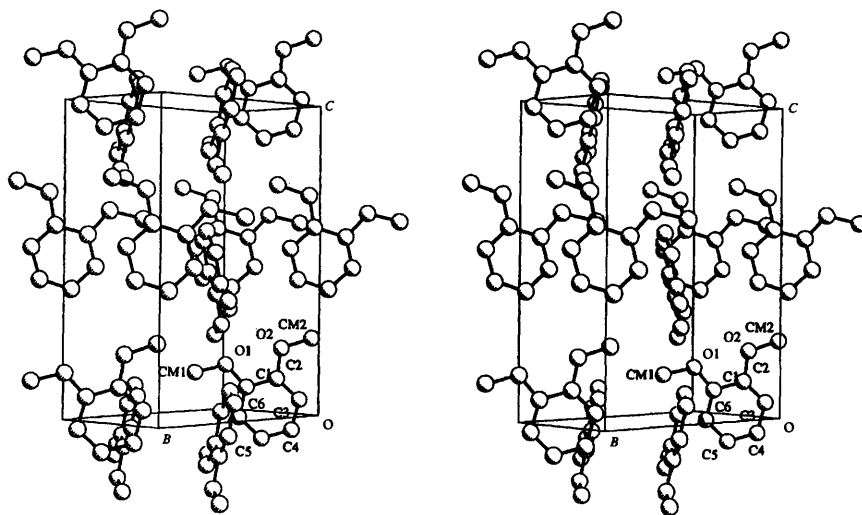


Fig. 3 Packing diagram of 1,2-DMB

Plane	Plane	Angle/°
A	B	77.90(9)
A	C	23.02(7)
A	D	73.19(8)
B	C	73.19(8)
B	D	23.02(7)
C	D	77.90(9)

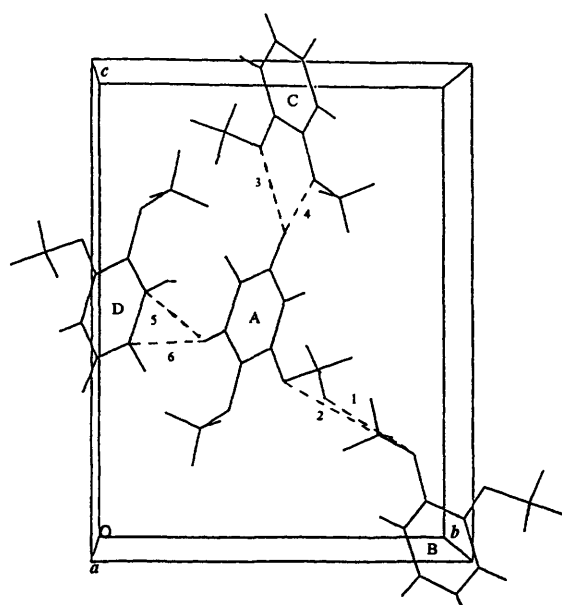


Fig. 4 Relative orientation of the molecules within the 1,2-DMB unit cell

ances at 110.4, 112.0 ppm and 121.1, 122.8 ppm are assigned to the *ortho* and *para* carbon atoms, respectively.

It has been demonstrated in 1,2-dialkoxybenzene moieties that twisting out of the plane by *ca.* 40° has little effect on the *para* carbon shifts whereas the *ortho* carbons, being more sensitive to the steric environment, are deshielded by *ca.* 5–6 ppm.^{47,48} Similarly the methoxy carbon of anisole becomes deshielded as the twist angle increases, based on *ab initio* LORG calculations.²⁴ In order to assess whether these trends are operative, *ab initio* shifts were calculated for 1,2-DMB with the GIAO³⁷ and LORG³⁸ methods using the X-ray data as input (Table 2). The results consistently show the most shielded *ortho* and methoxy carbons associated with the most out-of-plane O1–CM1, $\theta = 8.6^\circ$. Clearly these calculated

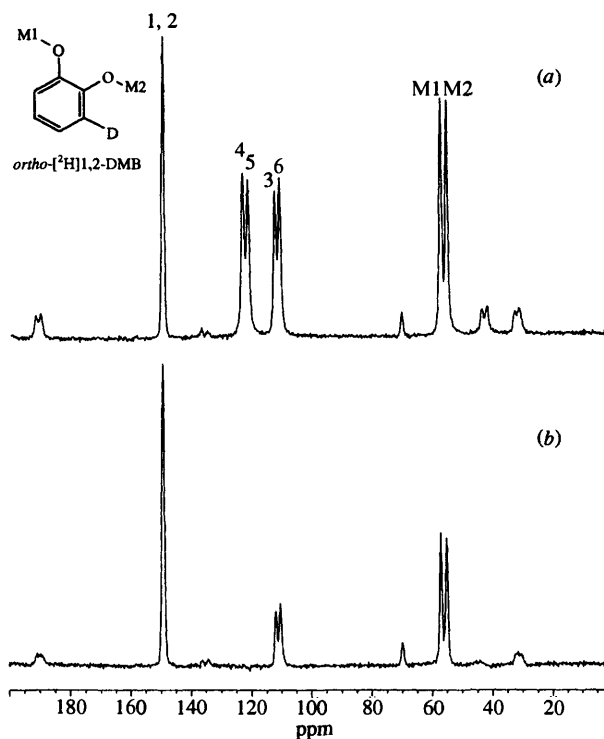


Fig. 5 (a) Normal and (b) dipolar dephased ¹³C CP MAS NMR spectra of *ortho*-[²H]1,2-DMB at 260 K

Table 1 Closest intermolecular X...H contacts in the 1,2-DMB unit cell

Contact	Numbering scheme	Distance/Å
O2...HM1B	1	2.30
O1...HM2C	2	2.70
O1...H5	3	2.59
O2...H5	4	2.68
C3...H3	5	2.82
C4...H3	6	2.88

shielding trends in solid 1,2-DMB are not consistent with intramolecular effects.

Theoretical calculations have shown the conformational preferences of 1,2-DMB have an impact on the geometry of the methoxy group and aromatic ring¹⁹ and in turn, solvation effects can overcome the energy difference between planar and

Table 2 Experimental and theoretical ^{13}C NMR principal chemical shifts of 1,2-DMB

		C1	C2	C3	C4	C5	C6	CM1	CM2
Solution ^a	σ_{iso}	149.1	149.1	111.4	120.9	120.9	111.4	55.7	55.7
Solid	σ_{iso}	149.4	149.4	112.0	122.8	121.1	110.4	55.0	56.9
	σ_{11}	209	209	185	215	210	184	82	84
	σ_{22}	168	168	137	139	134	134	68	68
	σ_{33}	71	71	14	14	19	13	15	19
LORG, D95V	σ_{iso}	157.4	158.4	117.9	128.7	122.4	112.7	52.8	56.8
	σ_{11}	236.9	240.0	218.9	246.2	237.2	213.6	79.6	81.1
	σ_{22}	167.8	170.3	130.7	132.4	129.6	125.5	70.1	75.5
	σ_{33}	67.4	64.8	4.2	7.4	0.4	-0.9	8.8	13.9
GIAO, 6-31G*	σ_{iso}	142.9	142.9	102.1	113.3	108.0	99.6	48.8	52.3
	σ_{11}	201.8	198.2	185.2	209.0	204.4	181.8	78.6	78.6
	σ_{22}	159.8	162.5	119.6	124.1	120.5	120.0	68.6	73.3
	σ_{33}	67.2	68.1	1.4	6.7	-0.8	-3.1	-0.7	5.1

^a Solution: 0.1 M in CDCl_3 .**Table 3** ^{13}C CP MAS NMR principal chemical shifts of several methoxybenzenes

	C1	C2	C3	C4	C5	C6	CM1	CM2	CM3
MB									
σ_{iso}	159.5	117.4	129.6 ^a	121.0	131.0 ^a	110.2	52.8		
σ_{11}	236	195	—	214	—	—	—		
σ_{22}	168	133	—	138	—	—	—		
σ_{33}	75	24	—	11	—	—	—		
1,2-DMB									
σ_{iso}	149.4	149.4	112.0	122.8	121.1	110.4	55.0	56.9	
σ_{11}	209	209	185	215	210	184	82	84	
σ_{22}	168	168	137	139	134	134	68	68	
σ_{33}	71	71	14	14	19	13	15	19	
1,3-DMB									
σ_{iso}	160.4	101.1	160.4	109.4	129.8	101.1	54.0	54.0	
1,4-DMB									
σ_{iso}	154.0	117.7	112.0	154.0	117.7	112.0	54.8	54.8	
σ_{11}	230	194	186	230	194	186	82	82	
σ_{22}	159	131	137	159	131	137	67	67	
σ_{33}	73	28	13	73	28	13	15	15	
1,3,5-TMB									
σ_{iso}	162.2	98.7	162.2	87.9	162.2	93.1	54.7	54.7	54.7
σ_{11}	242	155	242	151	241	152	87	87	87
σ_{22}	168	107	168	110	168	107	65	65	65
σ_{33}	77	34	77	3	77	20	12	12	12

^a Possible interchange of assignments.

non-planar conformers. Therefore packing forces are expected to be of sufficient relative magnitude to distort locally the molecule and this is reflected as CP MAS multiplicities. The inter-aromatic contacts are deemed to be of the C-H... π -type as found in other systems.^{27,49}

^{13}C Shielding tensor analysis[¶]

In order to obtain shielding tensor measurements a static solid is required or some degree of order in the tumbling motions of the solid. Using variable spinning CP MAS at 260 K the principal shielding tensors were measured for 1,2-DMB (Fig. 6).³³

Tensor measurements on 1,4-DMB and 1,3,5-TMB (both planar, X-rays known) were also measured and found to be ± 3 and ± 2 ppm, respectively, from the literature single crystal-derived tensors.³² The C3 sites of 1,2-DMB and 1,4-DMB are

γ -eclipsed by an *ortho* methoxy group to within a 5° torsion, hence are expected to be iso-electronic. Indeed there is only a 1 ppm difference between the respective principal tensors of these two molecules at this site (Table 3).

Low temperature measurements were also attempted on MB and 1,3-DMB and it was possible to extract tensor values for three MB sites; C1 (*ipso*), C2 (*ortho-trans*) and C4 (*para*). Tensor comparison of these MB sites to C1 of 1,3,5-TMB, C2 of 1,4-DMB and C5 of 1,2-DMB respectively (Fig. 7, Table 3), clearly support MB as a planar molecule.

By parametrizing the observed shieldings of these four methoxybenzenes in terms of *ipso*, *ortho-trans*, *ortho-cis*, *meta*, *para* relative to a planar methoxy and ϕ (the benzene parent) one may set up a series of equations. Considering the aromatic sites for which tensor data were experimentally determined^{||}

[¶] Experimental and calculated ^{13}C shift tensors and ^{13}C CP MAS spectra have been deposited as supplementary data; Suppl. Pub. 57183 (21 pp.). For details of the British Library Supplementary Publications scheme see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1995, issue 1.

^{||} This parametrized incremental shielding analysis takes into account those sites which have similar steric environments as MB therefore the C1, C2 sites of 1,2-DMB and C4, C6 sites of 1,3,5-TMB are excluded (Fig. 7). Note the average C3, C6 and C4, C5 anisotropic values of 1,2-DMB are used subsequently since there is no conformational basis for assignments.

(Fig. 7), one obtains three systems of equations each of which yield the shielding tensors for static benzene. The averaged values are $\sigma_{11} = 222$, $\sigma_{22} = 147$, $\sigma_{33} = 14$ with $\sigma_{\text{iso}} = 128$, which are quite close to the literature values (Table 4). Subtraction of the benzene values from the C1, C2 and C4 sites of MB give the *ipso*, *ortho-trans* and *para* shielding of a planar methoxy group. The differences between these and the related sites; C1 of 1,3,5-

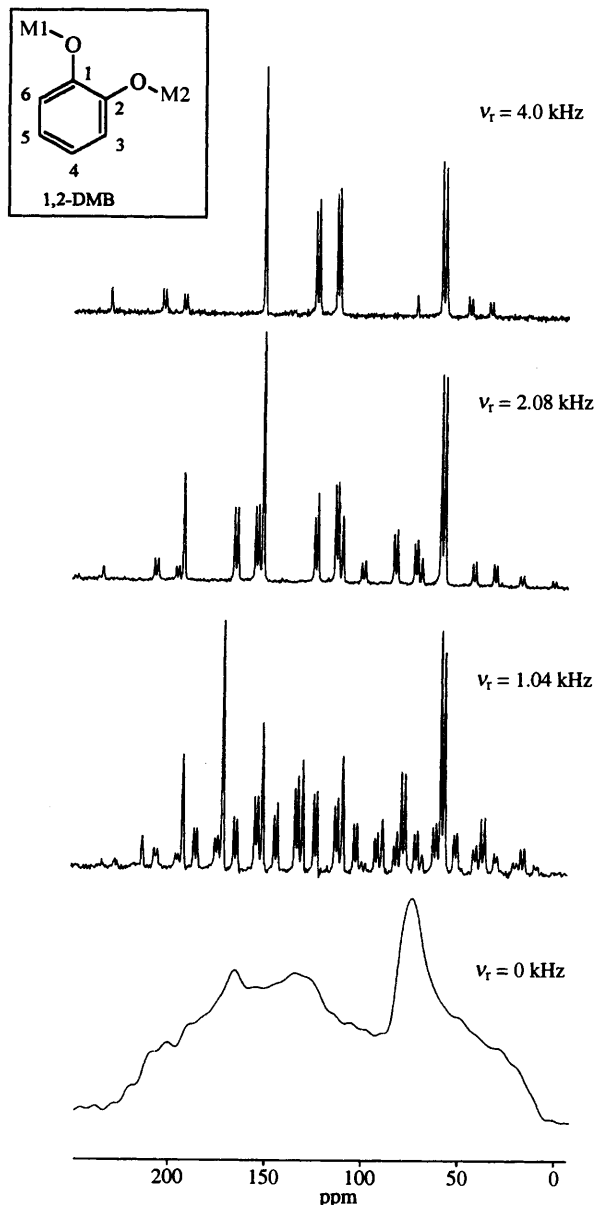


Fig. 6 Variable spinning rate ^{13}C CP MAS NMR spectra of 1,2-DMB at 260 K

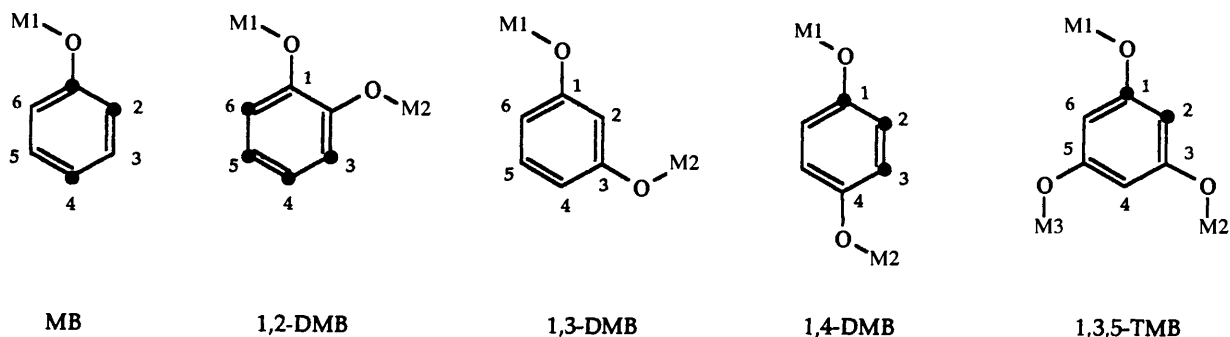


Fig. 7 Solid-state conformations of some planar methoxybenzenes

TMB, C2 of 1,4-DMB, C5 of 1,2-DMB can then be averaged to obtain the *meta* shielding. The *ortho-cis* effect was calculated by subtracting the benzene and *meta* values from the averaged C3 sites of 1,2-DMB and 1,4-DMB (Table 5).

For a planar methoxy substituent the *ipso* position is greatly deshielded in the σ_{33} direction by 60 ppm due to the σ inductive effect of the electronegative oxygen. This carries through to the *ortho-trans* position where the σ_{33} is still deshielding. The *ortho-trans* and *ortho-cis* isotropic values are -10 and -17 ppm, respectively. The 7 ppm extra *ortho-cis* shielding originates mainly from the σ_{33} direction which is consistent with an in-plane steric compression of the σ $\text{C}_{\text{ar}}\text{-H}$ electrons.⁵⁰ The shielding at the *para* site is due mainly to the σ_{11} and σ_{22} components which supports the π -donor resonance model of a methoxy group. The *meta* effect is the smallest consistent with the σ -acceptor and the π -donor behaviour of the methoxy group.

Low temperature CP MAS on MB and 1,3-DMB

For planar MB it is anticipated that seven lines will be resolved in the 210 K ^{13}C CP MAS spectrum and indeed at 4.5 kHz this is observed (Fig. 8). The shoulder on the methoxy peak indicates the presence of two conformers, but without an X-ray study one cannot speculate any further. From the CP MAS spectrum of 1,3-DMB at *ca.* 150 K (Fig. 9) the isotropic shifts are reported (Table 3). Both methoxy carbons resonate at 54.0 ppm, a value characteristic of planarity. Utilizing the isotropic SCS parameters (Table 5) two of the three possible planar conformers are quickly ruled out. 1,3-DMB adopts the asymmetric planar conformation in the solid state (Fig. 7).

Conclusions

In summary the solid phase spectral multiplicities of 1,2-DMB reflect crystal packing forces and are consistent with the observation that the asymmetric unit in the crystal is one molecule.

The C1, C2 sites of 1,2-DMB exhibit isotropic, but not anisotropic SCS additivity. Here the differences between the experimental and calculated σ_{11} , σ_{22} and σ_{33} values are 1, 10 and 11, respectively. If anisotropic additivity were upheld, the C1-C2 bond would be relatively σ -electron deficient, due to the inductive effect of the oxygens acting on the *ipso* and *ortho* sites. The offsetting nature of σ_{22} and σ_{33} reveals a compensatory distribution of π and σ density in the C1-C2 bond. Therefore both additive and non-additive anisotropic shifts can be rationalized in a manner consistent with the 3D electronic structure.

Experimental

All the chemicals were purchased from Aldrich.

Synthesis

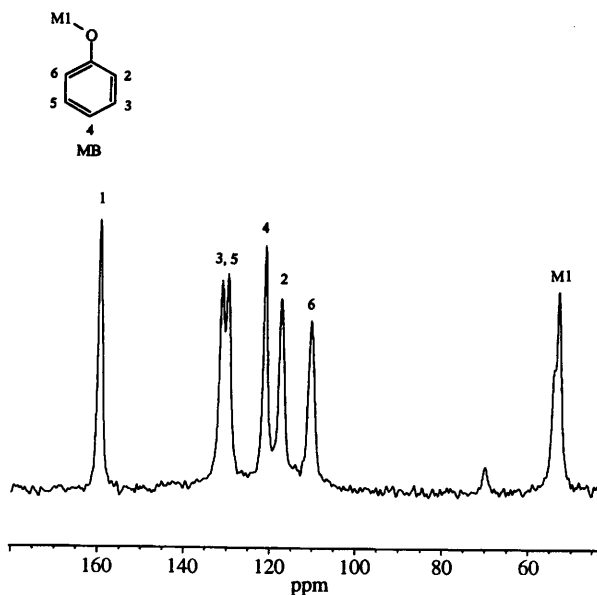
ortho-[^2H]1,2-DMB. All glassware was flame dried. To a suspension of Bu^tOK (2.24 g, 20 mmol) in 40 ml of anhydrous THF (previously distilled over LiAlH_4) was added BuLi (2.0 M

Table 4 ^{13}C NMR principal chemical shifts of benzene

	σ_{11}	σ_{22}	σ_{33}	σ_{iso}
CP at 223 K ^a	191	191	11	131
CP at 14 K ^b	217	140	1	119
CP at 20 K ^c	234	146	9	130
This study	222	147	14	128

^a Ref. 36. ^b Ref. 35. ^c Ref. 34.**Table 5** ^{13}C NMR principal substituent chemical shifts^a of a planar methoxy group

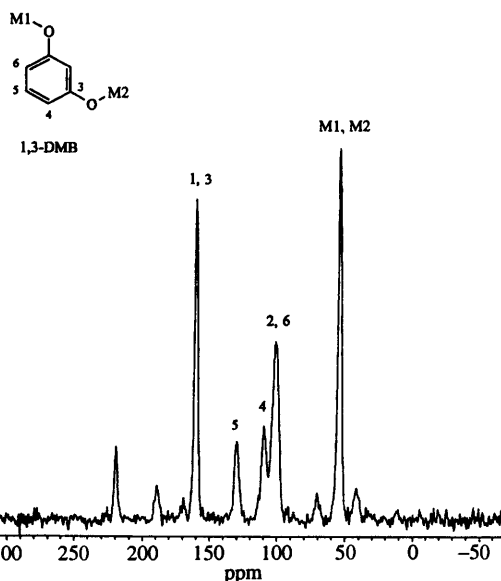
	σ_{11}	σ_{22}	σ_{33}	σ_{iso}
<i>ipso</i>	13 ± 2	-21 ± 1	60 ± 3	132 ± 2
<i>ortho-cis</i>	-36 ± 3	-9 ± 2	-5 ± 3	-17 ± 2
<i>ortho-trans</i>	-27 ± 2	-14 ± 1	9 ± 3	-10 ± 2
<i>meta</i>	-1 ± 1	-1 ± 1	4 ± 2	-1 ± 2
<i>para</i>	-8 ± 2	-9 ± 1	-3 ± 2	-7 ± 2

^a In ppm from solid benzene at $\sigma_{11} = 222$, $\sigma_{22} = 147$, $\sigma_{33} = 14$ and $\sigma_{\text{iso}} = 128$.**Fig. 8** ^{13}C CP MAS NMR spectrum of MB at 210 K

in pentane, 10 ml, 20 mmol) at -78°C . Then 1,2-DMB (1.38 g, 10 mmol) in 20 ml tetrahydrofuran (THF) was added with a syringe through a septum. After 15 min of stirring at -78°C the reaction mixture was quenched with D_2O and the reaction flask allowed to warm slowly to room temperature. After diluting with H_2O the product was partitioned into CH_2Cl_2 and the organic layer was washed with 2% KOH, saturated NaCl solution and dried over Na_2SO_4 . The solvent was removed by rotary evaporation. The crude material was purified by column chromatography on silica (grade 60, 230–400 mesh) using hexane–diethyl ether, 2:1, to give 0.89 g of *ortho*-[^2H]1,2-DMB, 64% yield with >95% deuterium incorporation. ^1H NMR; $\delta_4 = \delta_5 = 6.91$; $\delta_6 = 6.88$; $^3J_{\text{H}4-\text{H}5} = ^3J_{\text{H}5-\text{H}6} = 8.0$ Hz; $^5J_{\text{H}4-\text{H}6} = 2.0$ Hz; H–H coupling simulated by the LAOCOON program.⁵¹

Solid-state experiments

The ^{13}C CP MAS spectra were acquired at 50.32 MHz on a Bruker ASX-200 solid-state NMR spectrometer, equipped with a Bruker 7 mm triple resonance MAS probe. The magic angle was accurately set using the ^{79}Br resonance of KBr by maximizing the number of rotational echoes in the free induction decay. The ^1H 90° pulse lengths were typically 4.2 μs with a delay time of 60.0 s for 1,2-DMB at 260 K; 5 s for 1,4-DMB and 1,3,5-

**Fig. 9** ^{13}C CP/MAS NMR spectrum of 1,3-DMB at 150 K

TMB at room temperature; 2 s for MB at 210 K. The chemical shifts were externally referenced to the ^{13}C resonance of tetraakis(trimethylsilyl)silane $\text{Si}[\text{Si}(\text{CH}_3)_3]_4$, which was assigned a chemical shift of 3.7 ppm (with respect to TMS). The spin rates were typically between 4 and 6 kHz and were stable to within a couple of Hz. The experiments achieved at various temperatures for 1,2-DMB were conducted by driving the spinner with cold N_2 gas. ^{13}C CP MAS spectra of 1,3-DMB were recorded at 45.3 MHz on a Bruker CXP-180 with 3.6 μs for the 90° pulse, a delay of 2–4.0 s and a contact time of 3.5 ms at ca. 150 K. Chemical shifts were measured relative to hexamethylbenzene (HMB) and converted to the TMS scale via a factor of 16.9 ppm, which is the chemical shift for the CH_3 group of HMB. The ^{13}C CP MAS dipolar diphased spectrum of *ortho*-[^2H]1,2-DMB was recorded with a dephasing delay of 40 μs .

Crystallographic data

1,2-DMB (lit. mp = 15°C)¹⁶ was purchased from Aldrich and purified by distillation. Suitable crystals in the form of needles were obtained by slow crystallization from anhydrous pentane in a freezer at -5°C . Further work was achieved in a cold room at $+4^\circ\text{C}$ where the crystals were filtered by suction, washed with aliquots of cold pentane and kept sealed under nitrogen in a freezer. The mounting on the X-ray axis was achieved using epoxy glue which was first allowed to harden in the cold room for 5 min. The intensity data were obtained at -120°C with a Nonius diffractometer using the $\theta/2\theta$ scan mode. All atoms were refined anisotropically except hydrogens, which were refined isotropically. The protons HM1B and HM2A were found and the other methoxy hydrogen positions calculated. Weights based on counting statistics were used and all calculations performed using the NRC/VAX crystallographic software package.^{52–53}

Computations

LOGR. The X-ray coordinates were used as input into the QUANTA/CHARMM⁵⁴ molecular modelling program and where necessary hydrogen atoms were added using CHARMM force field parameters. The resulting Z-matrix was then used as input for an *ab initio* RH SCF calculation in the program GAMESS⁵⁵ using the D95V basis set. The post SCF NMR shielding tensor calculations were done using the RPAC³⁸ program using the no-sort option for the localization of orbitals.

GIAO. The theoretical NMR chemical shifts were calculated using the Gaussian 94 program³⁷ using 6-31G* basis sets for all the atoms. Test calculations using much larger basis sets

show the 6-31G* basis set is adequate in providing relative chemical shifts. The ground-state wavefunctions were computed within the gradient corrected local density (LDA) functional B3LYP approximation. The Gauge Invariant Atomic Orbital (GIAO) method was used in the calculation of the chemical shielding. A recent study has shown that a combination of B3LYP and GIAO using 6-31G* basis set is able to provide reasonable chemical shifts for a variety of molecules.⁵⁶ The calculations were performed at the X-ray determined structure. The results on the ¹³C shifts are presented relative to tetramethylsilane (TMS) computed using a similar procedure (191.1 ppm relative to the bare nucleus).

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