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A CONFORMATIONAL STUDY OF BIS-, TRIS- AND TETRAKIS-PYRAZOLYLMETHANE. CRYSTALLOGRAPHY, L.S.R., DIPOLE MOMENTS AND THEORETICAL CALCULATIONS

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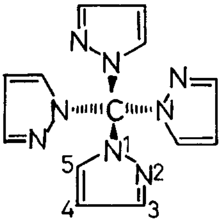
Theoretical calculations (MM2 and MNDO) have been carried out on several conformations of bis-, tris- and tetrakispyrazolylmethane. The potential surface thus obtained has been compared with experimental results both in solution (lanthanide shift reagents, dipole moments) and in the solid state (crystallography). The structure of tetrakispyrazolylmethane (3) was determined by X-ray diffraction. The com pound crystallizes in the C2/c space group, with a cell of dimensions 29.5117(14), 6.9815(2), 13.8903(4) Å and 105.237(3)°. The molecule presents an approximate $S_4(\bar{4})$ axis such as N12, N22, N32 and N42 form a distorted tetrahedron. The calculated conformations of minimum energy are consistent with dielectric measurements. The structure of 3 in the solid state lies 5.0 kcal.mol^{-1} above the minimum as a result of the crystal field. To explain the LSR results, a coordination with two pyrazole nuclei has to be assumed. The presence of a metal (LSR, organometallic complexes) strongly modifies the conformation: in these conditions, bidentated and tridentated structures are observed.

The stereochemistry of polyarylmethanes has been masterly studied by Mislow and coworkers.[1,2] No related work on polyheteroarylmethanes has been carried out. We report here a conformational analysis of bispyrazolylmethane (1), trispyrazolylmethane (2) and tetrakispyrazolylmethane (3). From a symmetry point of view, they are equivalent to poly-o-tolylmethanes,[1] but with two important differences: Csp^3-Nsp^2 instead of Csp^3-Csp^2 central bonds and pyridine-like ortho nitrogen atoms which are worth of study.



Bispyrazolylmethane (1) : B, D ≡ H

Trispyrazolylmethane (2) : D ≡ H

Tetrakispyrazolylmethane (3)

SOLID STATE STUDY

Crystal and Molecular Structure of Tetrakis(pyrazol-1-yl)methane (3)

Table 1 presents a selection of the geometrical characteristics describing this molecule in the crystal, as can be seen in Fig. 1. The C1 atom presents a distorted sp^3 geometry, with N-C-N angles ranging from 108.7(2) to 110.4(2)°. For the four heterocycles, the Csp^3-N-C angles are larger than the Csp^3-N-N ones.

Table 1. Selected geometrical parameters (Å, °)

i=	1	2	3	4						
C1-Ni1	1.443(3)	1.453(3)	1.445(4)	1.443(4)	N11-C1-N21	110.4(2)	N11-C1-N31	109.2(2)	N11-C1-N41	108.8(2)
Ni1-Ni2	1.356(3)	1.352(5)	1.352(4)	1.358(4)	N21-C1-N31	108.7(2)	N21-C1-N41	109.6(2)	N41-C1-N31	110.1(2)
Ni2-Ci3	1.310(6)	1.319(6)	1.320(6)	1.317(5)	N12...N22	4.361(5)	N12...N32	4.389(4)	N12...N42	2.915(5)
Ci3-Ci4	1.362(9)	1.347(8)	1.371(7)	1.373(6)	N22...N32	3.022(6)	N22...N42	4.319(5)	N32...N42	4.325(5)
Ci4-Ci5	1.357(6)	1.356(6)	1.359(6)	1.347(6)	N12..C1..N22	129.3(2)	N12..C1..N32	130.9(2)	N12..C1..N42	74.2(1)
Ci5-Ni1	1.354(5)	1.331(5)	1.342(5)	1.346(4)	N22..C1..N32	77.5(2)	N22..C1..N42	126.6(2)	N32..C1..N42	127.0(2)
C1-Ni1-Ni2	119.0(3)	118.8(3)	119.3(2)	119.4(2)	N31-C1-N11-N12	-83.3(3)	N41-C1-N21-N22	-166.6(3)		
C1-Ni1-Ci5	128.3(3)	130.1(3)	128.6(3)	129.3(3)	N11-C1-N31-N32	-168.1(3)	N21-C1-N41-N42	-71.4(3)		
Ci5-Ni1-Ni2	112.3(3)	111.1(3)	112.1(3)	111.2(3)	N21-C1-N11-N12	157.2(3)	N31-C1-N41-N42	169.1(2)		
Ni1-Ni2-Ci3	104.0(4)	104.2(4)	103.8(3)	104.4(3)	N11-C1-N21-N22	73.6(3)	N41-C1-N31-N32	72.5(3)		
Ni2-Ci3-Ci4	112.0(4)	112.2(4)	112.3(4)	111.7(4)	N41-C1-N11-N12	36.9(3)	N21-C1-N31-N32	-47.6(3)		
Ci3-Ci4-Ci5	107.0(5)	105.7(4)	105.4(4)	106.0(4)	N11-C1-N41-N42	49.4(3)	N31-C1-N21-N22	-46.2(4)		
Ci4-Ci5-Ni1	104.8(4)	106.9(3)	106.4(3)	106.8(3)						

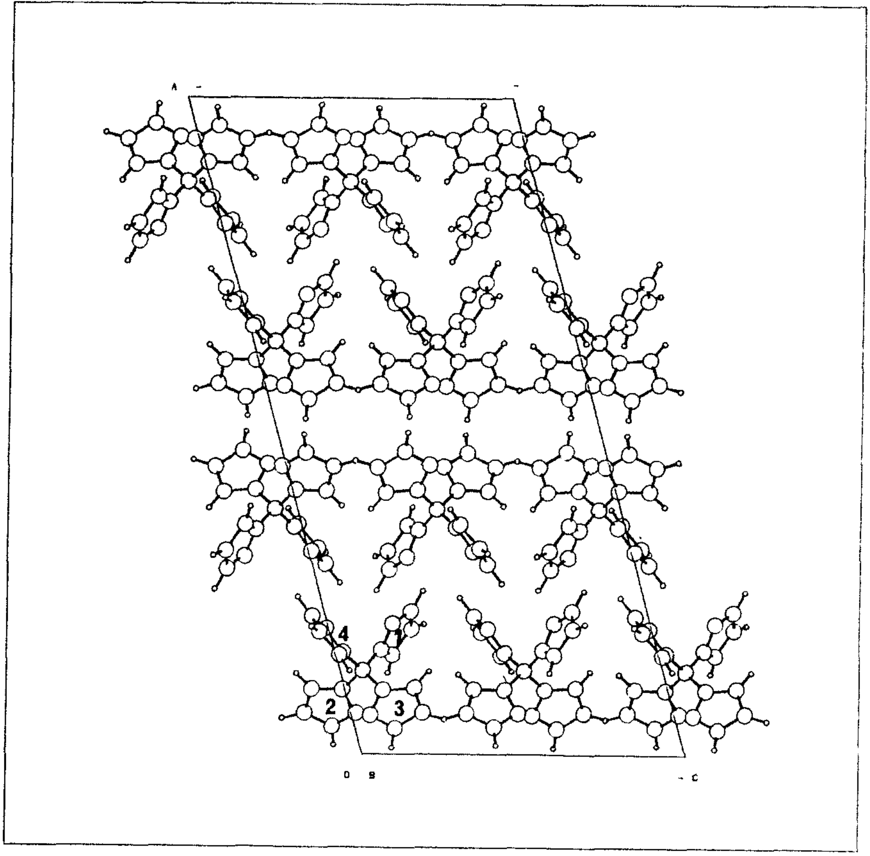


Fig. 1. The packing of the structure is shown along the b axis (A ≡ 10's; B ≡ 20's; C ≡ 40's; D ≡ 30's)

The molecule (3) can be described as presenting a distorted S_4 conformation, with the pseudo four-fold inversion axis bisecting N11-C1-C41 and N21-C1-N31 (the N-C-N-N torsion angles range from 36.9(3) to 49.4(3)°). Thus, the Ni2 (i = 1,4) atoms form a distorted tetrahedron, with the N···N distances and the N···C1···N angles ranging from 2.915(5) to 4.389(4) Å and 74.2(1) to 130.9(2)°, respectively. Along the c axis (see Fig. 1), the crystal packs its molecules in two series through some contacts shown in Table 2.

Table 2. Selected intermolecular contacts (Å)

H13 ··· N12	(1/2-x,	-1/2+y,	1/2-z)	=	3.20(5)
H14 ··· N12	(1/2-x,	-1/2+y,	1/2-z)	=	3.21(7)
H14 ··· N42	(x,	-y,	1/2+z)	=	3.04(8)
H43 ··· N12	(1/2-x,	1/2-y,	-z)	=	3.21(5)
H43 ··· N42	(1/2-x,	1/2-y,	-z)	=	2.83(5)
H23 ··· N22	(-x,	-y,	-z)	=	2.66(6)
H23 ··· N32	(-x,	-y,	-z)	=	3.22(5)
H34 ··· N32	(-x,	1-y,	-z)	=	2.71(4)

SOLUTION STUDIES

^{1}H N.m.r.: Lanthanide Shift Reagents [Eu(fod)$_3$] Induced Shifts in $CDCl_3$

A comparative study has been carried out on the three compounds, **1-3**, and on N-methylpyrazole (**4**). We have explored LSR/substrate ratios between 0 and 1. For high L/S ratios the usual downwards curvature is observed. The slopes have been calculated by the gradient method[3] using the linear part of the plot. In Table 3 are gathered the relative slopes. The most sensitive protons are either those linked to C3 or those linked to C1. In order to compare all compounds, including 3 which lacks Csp^3 protons, the relative values for heterocyclic protons have also been calculated.

Table 3. LIS of pyrazole derivatives

Compound	$C(sp^3)H_n$	H3	H4	H5	CH_n	H3	H4	H5
4	n = 3	100	35.9	38.2	87.5	100	35.9	38.2
1	n = 2	8.3	18.9	37.7	100	22.0	50.1	100
2	n = 1	18.6	12.4	25.0	100	74.4	49.6	100
3	n = 0	----	----	----	----	100	27.7	84.1

We have represented in Fig. 2 a set of possible conformations which could account for the observed effects (for the definition of φ angles, see later on theoretical calculations). Although no quantitative attempt to situate the europium has been made, the conformations of Fig. 2 are consistent with the McConnell-Robertson picture, provided that the principal magnetic axis in N-methylpyrazole is situated like in pyridine (along an imaginary N2-Eu bond)[3] whereas in polypyrazolylmethanes it would be directed from the europium to the central sp^3 atom (similar to what has been proposed for carboxylic acid complexes).[3]

The problem of the influence of the shift reagent on the conformation of the ligands, i.e. whether the conformations depicted in Fig. 2 are or nor representative of those of the free ligands, will be discussed after the theoretical part.

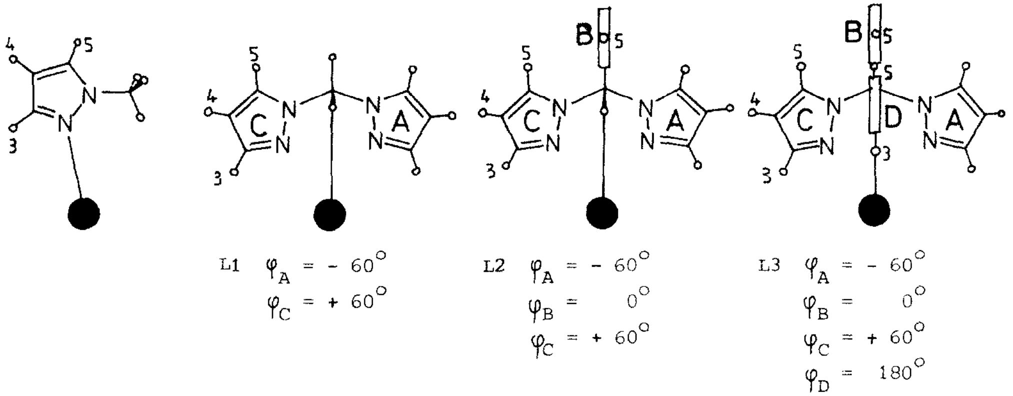


Fig. 2. Representation of the possible conformations in the LSR-substrate complexes

Dipole Moments in Benzene and Cyclohexane

The experimental dipole moments have been determined in benzene (compounds **1**-**4**) and in cyclohexane (compounds **1** and **2**) at 25°C by the Debye[4] and Guggenheim and Smith[5] methods (Table 4)

Table 4. Experimental dipole moments of pyrazole derivatives

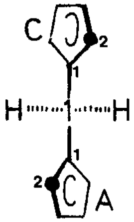
Compound	Solvent	α	β	$P_{2\infty}$	RM_D	$\mu(D)^{H-K}_{25^\circ C}$	$\mu(D)^{G-S}_{25^\circ C}$
4	Benzene	6.42	-0.12	124.22	24.26	2.20	2.21
1	Benzene	2.05	-0.27	95.54	40.89	1.61	1.63
1	Cyclohexane	2.50	-0.29	126.36	43.33	1.99	2.02
2	Benzene	3.81	-0.34	204.86	58.62	2.65	2.67
2	Cyclohexane	4.35	-0.42	270.90	59.73	3.19	3.22
3	Benzene	0.00	-0.32	69.02	67.87	0.00	0.00

THEORETICAL CALCULATIONS

Our approach to the problem has been to calculate most conformations by means of molecular mechanics (Allinger's MM2 method)[6] and, for some selected ones, to carry out MNDO calculations with complete optimization of the geometry.[7] Since the $N(sp^2)-C(sp^3)$ bond, typical of the compounds of this study, has not been parametrized until very recently,[8] the MM2 calculations were carried out with $C(sp^2)-C(sp^3)$ bonds of 1.497 Å of natural length, i.e. with "pyrrole-like" rings.

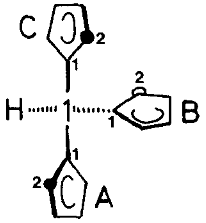
Definition of the Torsion Angles

We have adopted the following logical definition of the dihedral angles φ (in all cases, a positive value for φ means that the conformation is obtained from the $\varphi = 0^\circ$ conformation by a counterclockwise rotation of the pyrazole ring about the N-C bond).[9] The conformations represented below correspond to all φ dihedral angles equal to 0°.



φ_A = C1-1-A1-A2

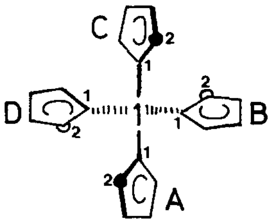
φ_C = A1-1-C1-C2



φ_A = C1-1-A1-A2

φ_C = A1-1-C1-C2

φ_B = H-1-B1-B2



φ_A = C1-1-A1-A2

φ_C = A1-1-C1-C2

φ_B = D1-1-B1-B2

φ_D = B1-1-D1-D2

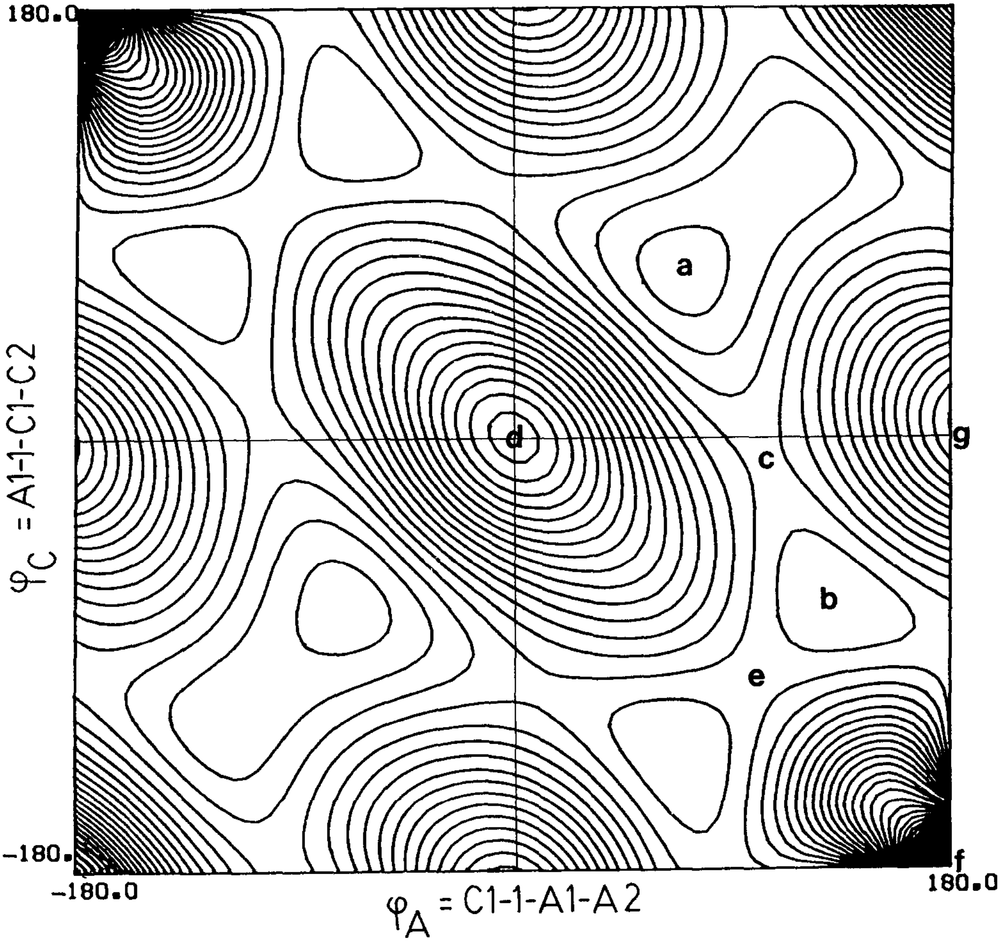


Fig. 3. MM2 potential energy surface of bispyrazolylmethane (1)

Bispyrazolylmethane (1)

The MM2 potential energy surface of this compound, as a function of φ_A and φ_C, is represented in Fig. 3. The surface has been generated from a grid of points separated by 15° (288 calculated points of a total of 576). The absolute minimum **a** is about 70/70° (φ_A/φ_C notation) and a second minimum is found at 130/-70° (0.5 kcal.mol^{-1} higher). The transition state **c**, 105/-10°, is 0.75 kcal.mol^{-1} above **a** and another transition state **e**, 100/-100°, is at 0.6 kcal.mol^{-1} above **a**. The 0/0° conformation **d** lies 4.5 kcal.mol^{-1} over the ground state and two other maxima are found at 180/180° (**f**, 5.8 kcal.mol^{-1}) and at 180/0° (**g**, 3.7 kcal.mol^{-1}). The **a** $\rightleftharpoons$ **a** isomerization (racemization) through **c** and **e** has a very low activation energy (0.75 kcal.mol^{-1}). The conformation deduced from the LSR experiments (Fig. 2) 60/-60°, lies ca 2 kcal.mol^{-1} higher than **a**. Conformations **a**, **b**, **c** and **d** were optimized within the MNDO approximation. The results are collected in Table 5.

Table 5. Results of MNDO calculations on bispyrazolylmethane

Conformation	φ_A	φ_B	ΔH_f(kcal.mol^{-1})		μ(D)	Pop. at 25°C
1a	93.6	90.8	95.74	(0)	0.69	98.46
1b	110.2	-79.2	98.26	(2.52)	3.49	1.39
1c	110.2	-12.6	99.99	(4.25)	2.97	0.14
1d	0	0	108.44	(12.70)	3.57	----

If the MNDO energies are compared with those obtained from the MM2 surface, a rough correlation is found for the four points of Table 5: ΔH_f(MNDO) = 1.1 + 2.6 ΔE(MM2), $r^2 = 0.97$. This allows an estimation of MNDO values all over the surface represented in Fig. 3 (MM2 separation between level lines is 0.25 kcal.mol^{-1}). For instance, the 60/-60° conformation should be 6 kcal.mol^{-1} above the MNDO minimum. Since the additive property is the square of the dipole moment, the averaged value for the most stable conformations, **1a** and **1b**, should be $\mu = \sqrt{0.9846 \times 0.69^2 + 0.0139 \times 3.49^2} = 0.80$ D. Since the experimental values (Table 4) are 1.62 (benzene) and 2.00 (cyclohexane), it seems that the differences in stability, calculated by MNDO, are overestimated. To be consistent with the experimental dipole moments, the proportions should be 82% **1a**-16% **1b** in benzene and 70% **1a**-30% **1b** in cyclohexane, i.e. 1a more stable than 1b by ca. 1 kcal.mol^{-1} in benzene and 0.5 kcal.mol^{-1} in cyclohexane, values closer to the MM2 calculations.

Trispyrazolylmethane (2)

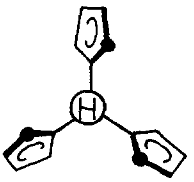
For this compound no systematic exploration of the hypersurface, $\Delta E = f(\varphi_A, \varphi_B, \varphi_C)$ has been carried out, but the four propellers minima and two singular points have been calculated by MNDO. The results are presented in Table 6.

The first four conformations, **2a-2d**, correspond to propeller structures, with pyridine-like nitrogens (N2) on the same side than CH, Z, or on the other side, E. Leaving aside the problem of optical isomerism, the propeller can be defined by the average angle of twist, $\bar{\theta}$, that the pyrazole ring makes with the N1-C1-H plane. According to this definition, these conformations can be described as **2a** = ZEZ ($\bar{\theta}$ = 19.2°), **2b** = ZEE ($\bar{\theta}$ = 22.6°), **2c** = ZZZ (θ = 30.8°) and **2d** = EEE ($\bar{\theta}$ = 35.0°).

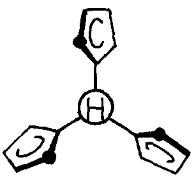
Table 6. Results of MNDO calculations on trispyrazolylmethane

Conformation	φ_A	φ_B	φ_C	ΔH_f(kcal.mol^{-1})	μ(D)	Pop. at 25°C
2a	136.9	-163.0	-96.5	154.80 (0)	2.03	61.83
2b	134.2	-154.4	86.8	155.09 (0.29)	2.14	37.89
2c	151.4	36.8	-95.9	157.42 (2.62)	3.82	0.25
2d	-25.1	-143.2	93.2	158.76 (3.96)	4.29	0.03
2e	60.0	0.6	-60.0	165.32	4.06	----
2f	-60.0	180.0	60.0	162.19	5.02	----

The two last conformations of Table 6 correspond to a bidentate conformation (**2e**, two lone pairs well-disposed to interact with a metal) and to a tridentate conformation (**2f**, the three lone pairs in the best position to interact with a metal).



ZZZ



$\bar{Z}\bar{Z}\bar{Z}$

The calculated dipole moment for a 61.83/37.89 mixture of the most stable conformers, **2a** and **2b**, is 2.07 D whereas the experimental values are 2.66 D (benzene) and 3.20 D (cyclohexane). Here again, the experimental values are larger than those calculated by MNDO, either because the high dipole moment conformations, **2c** and **2d**, have their energies overestimated or because MNDO underestimates the dipole moments of pyrazoles. To check this last possibility, the dipole moment of N-methylpyrazole (4) has been calculated. The MNDO value, 2.34 D, slightly overestimates the experimental one (Table 4, benzene, 25°C, 2.20 D, Lit.: benzene, 25°C, 2.25 D).[10]
The conformation deduced from the LSR studies corresponds to that of **2e**. In the optimization of this geometry, φ_B is free to take any value between 0 and 180°. With regard to this ring, the minimum has been found at 0.6°, which is in accord with the conformation represented in Fig. 2 (**L2**).

Tetrakispyrazolylmethane (3)

To make apparent the symmetry of the X-ray structure it is useful to select the following dihedral angles of Table 1: φ_A = -46.2, φ_B = 36.9, φ_C = -47.6, and φ_D = 49.4°.

Table 7. Results of MNDO calculations on tetrakispyrazolylmethane

Conformation	φ_A	φ_B	φ_C	φ_D	ΔH_f(kcal.mol^{-1})	μ(D)
3a	-126.1	128.1	-125.1	126.0	219.38	0.05
3b	-131.8	125.2	-133.2	149.0	220.63	0.63
3c	-149.7	136.7	-121.5	-38.6	222.46	3.13
3d	-141.0	135.4	21.4	-34.5	224.28	3.63
3e	-120.0	-58.1	-121.6	-57.8	225.68	2.75

.../...

Table 7. Continuation

3f	-123.2	34.5	-139.4	50.7	228.34	3.84
3g	-46.2	36.9	-47.6	49.4	224.39	0.29
3h	-107.9	107.9	-107.9	107.9	224.05	0.07
3i	-99.6	99.6	-99.6	99.6	224.87	0.07
3j	-79.8	79.8	-79.8	79.8	227.61	0.07
3k	0	17.6	0	-151.0	229.23	3.42
3l	0	0	0	0	230.43	0.30
3m	-60	180	60	-146.3	228.50	4.01
3n	180	180	180	180	236.04	0.24
3p	-60	128.1	60	58.8	226.10	3.52
3q	-60	0	60	180	232.17	4.59

The conformations **3a**-**3f** of Table 7 correspond to minimizations starting from different points of the hypersurface $\Delta E = f(\varphi_A, \varphi_B, \varphi_C, \varphi_D)$. Considering only the discrete values 0, 60, 90, 120, 180, -120, -90 and -60° for the dihedral angles, the conformations of Table 7 belong to the following classes: -120/120/-120/120, **3a** (Fig. 4) and **3b**; -120/120/-120/-60, **3c**; -120/120/60/-60, **3d**; -120/-60/-120/-60, **3e**; -120/60/-120/60, **3f**; -60/60/-60/60, **3g** (X-ray, Fig. 5); -90/90/-90/90, **3h**-**3j** (S_4); 0/.../0/..., **3k** (Bidentated); -60/.../60/..., **3p** (Bidentated); -60/0/60/180, **3q** (LSR, Fig. 2, L3); -60/180/60/..., **3m** (Tridentated); 0/0/0/0, **3l** (Double bidentated); 180/180/180/180, **3n**.

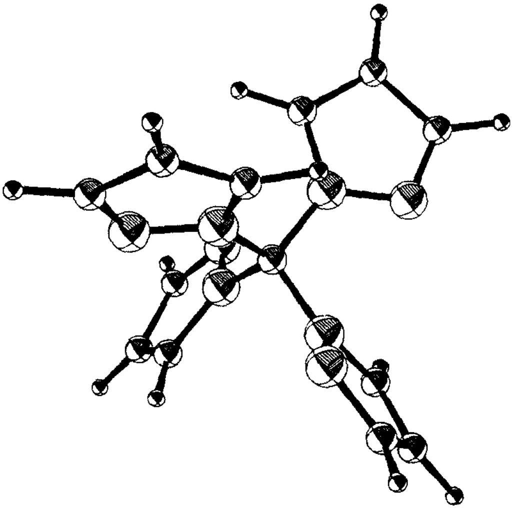


Fig. 4. Minimum energy conformation (**3a**)

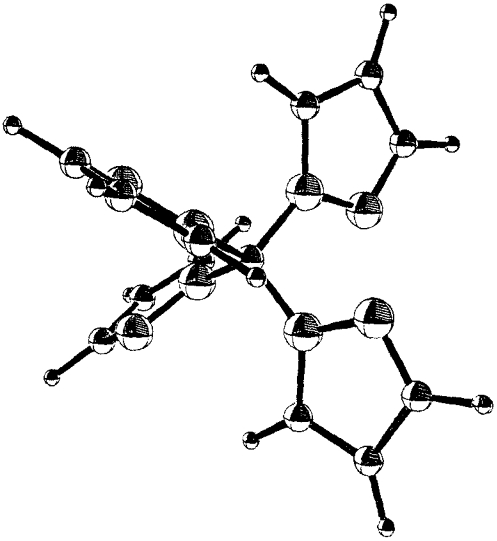


Fig. 5
Experimental X-ray conformation (**3g**)

The experimental dipole moment (0 D, Table 3) is in agreement with that of the minimum energy conformation **3a**, although other much less favorable conformations, like **3l**, also have very small calculated dipole moments. Conformations 3c-3f can be excluded owing to their high dipole moments.

The X-ray geometry, **3g**, lies in the path corresponding to a synchronous clockwise rotation of the four pyrazole rings: **3l** (0/0/0/0) $\longrightarrow$ **3g** (-45/45/-45/45) $\longrightarrow$ **3j** (-80/80/-80/80) $\longrightarrow$ **3h** (-108/108/-108/108) $\longrightarrow$ **3a** (-126/126/-126/126) $\longrightarrow$ **3n** (180/180/180/180). Conformations **3h-3j** correspond to the highest attainable symmetry for compound 3.[11] A simple mathematical calculation (which depends only on the X...C-N1 angle)[11] leads to Table 7 values: 107.9° when X = H5, 99.6° when X = C5 and 79.8° when X = N2. All these conformations are less stable than the $|\varphi| = 126^{\circ}$ and the stability decreases when $|\varphi|$ decreases, without modification of the dipole moment which remains consistent with the experimental result.

Among the singular points of the hypersurface, a number of conformations relevant for their complexing abilities were calculated. These include two bidentated conformations, **3k** and **3p** ($_A$ and $_D$ optimized), the tridentated one, **3m**, and the double bidentated one, **3l**. As in the case of compounds **1** and **2**, these conformations are not populated in the absence of a metal. The conformation deduced from LSR studies (L3, Fig. 2), **3q**, is 12.8 kcal.mol^{-1} less stable than **3a**.

CONCLUSIONS

The conformation of pyrazolylmethanes results from the balance of two effects: the repulsion of N2-N2 lone pairs and the steric effects between H5-H5 atoms. This results in the most stable conformations which could be termed "gauche": **1a**, **2a** and **3a**. The interactions H5···N2 are more favorable, but not enough to stabilize conformations like **2g** ($\varphi_A = 0$, $\varphi_C = 180^{\circ}$). This situation is dramatically modified in the presence of metals. The X-ray structures of rhodium(I) complexes of bispyrazolylmethane **1** and trispyrazolylmethane **2** have been determined.[12,13] Described in terms of dihedral angles, the X-ray structures correspond to **1**Rh, $\varphi_A = -56.6$, $\varphi_B = 55.5^{\circ}$;[12] **2**Rh, $\varphi_A = -61.7$, $\varphi_B = 177.5$, $\varphi_C = 60.4^{\circ}$.[13] The first one corresponds to L1 (Fig. 2) and the second one has φ_A and φ_C like L2, but φ_B in the rhodium complex corresponds to a tridentated complex whereas the LSR can coordinate only with two pyrazoles to form an eight-coordinated complex. According to preliminary n.m.r. results, tetrakispyrazolylmethane **3** yields with Rh(I) and Ir(I) tridentated complexes and not double-bidentated ones.[14] The reason is that conformations with $\varphi_A = \varphi_C = 0^{\circ}$ (**1d**, **3k** and **3l**) have a geometry that cannot accomodate a metal without a considerable deformation of N2-metal angles (N1-N2-M = 155° and N2···M···N2 = 60° for a N2-M distance of 2.15 Å) whereas conformations with $\varphi_A = -60^{\circ}$, $\varphi_C = 60^{\circ}$ (**L1**) and $\varphi_B = 180^{\circ}$ (**2f** and **2m**) correspond to N1-N2-M = 120° and N2···M···N2 = 85°. These last values are similar to those observed for monodentated pyrazole complexes, where the pyrazole ligands are free to adopt the most favorable position.[15]

EXPERIMENTAL SECTION

The products here discussed have been prepared according to literature procedures: **1**,[16]

Table 8. Crystal analysis parameters at room temperature

Crystal data

Formula	$C_{13}H_{12}N_8$
Crytal habit	Colourless, transparent, plate
Crystal size (mm)	0.40 x 0.23 x 0.10
Symmetry	Monoclinic, C2/c
Unit cell determination:	Least-squares fit from 68 reflexions ($\theta < 45°$)
Unit cell dimensions	29.5117(14), 6.9815(2), 13.8903(4)Å 90, 105.237(3), 90 °
Packing: V(Å^3), Z	2761.3(2), 8
Dc(g.cm^{-3}), M, F(000)	1.348, 280.29, 1168
μ(cm^{-1})	7.041

Experimental data

Technique	Four circle diffractometer: Philips PW1100 Bisecting geometry Graphite oriented monochromator :CuK$_\alpha$ $\omega/2\theta$ scans, scan width :1.5° Detector apertures 1 x 1°, up θmax. 65° 1 min./reflex.
Number of reflexions :	
Measured	2661
Independent	2332
Observed	1698 (3σ(I))
Standard reflexions :	2 reflexiones every 90 minutes Variation : no

Solution and refinement

Solution	Direct Methods
Refinement	L.S. on Fobs with 1 block
Parameters :	
Number of variables	238
Degrees of freedom	1460
Ratio of freedom	7.1
H atoms	Difference synthesis
Final shift/error	0.05
w-scheme	Empirical as to give no trends in <wΔ^2F> vs. <|Fobs|> and <sin θ)/λ>
Max. thermal value	U22(N42)=0.160(4)Å^2
Final ΔF peaks	0.24 eÅ^{-3}
Final R and Rw	0.065, 0.076
Computer and programs	Vax11/750, XRAY76[19], MULTAN80[20]
Scattering factors	Int. Tables for X-Ray Crystallography[21]

Table 9. Final atomic coordinates

Atom	x/a	y/b		Atom	x/a	y/b	z/c
C1	0.12787(9)	0.26247(41)	0.06901(20)	N31	0.09802(7)	0.37302(38)	0.11551(18)
N11	0.15936(7)	0.14713(36)	0.14378(17)	N32	0.06031(10)	0.46463(58)	0.05743(24)
N12	0.19944(9)	0.22717(52)	0.20022(24)	C33	0.06421(15)	0.50644(71)	0.21892(37)
C13	0.21752(15)	0.09378(91)	0.26530(30)	C34	0.04059(14)	0.54605(65)	0.12206(38)
C14	0.19008(20)	-0.06587(92)	0.25306(37)	C35	0.10114(12)	0.39488(58)	0.21302(27)
C15	0.15240(16)	-0.03178(57)	0.17474(34)	N41	0.15529(7)	0.38867(34)	0.02424(17)
N21	0.09851(8)	0.14127(39)	-0.00744(18)	N42	0.19116(9)	0.31573(44)	-0.00876(24)
N22	0.06334(12)	0.04118(67)	0.01461(27)	C43	0.20969(13)	0.46593(64)	-0.04138(26)
C23	0.04292(15)	-0.04838(66)	-0.06914(37)	C44	0.18632(14)	0.63160(66)	-0.03104(29)
C24	0.06352(15)	-0.00830(71)	-0.14257(39)	C45	0.15185(12)	0.57954(49)	0.01080(26)
C25	0.09893(13)	0.11495(61)	-0.10211(28)				

2,[17] 3,[17] and 4.[18]

Crystal Structure Determination

Table 8 summarizes the crystal analysis parameters and Table 9 displays the final atomic coordinates for all non-hydrogen atoms.

Lanthanide Shift Reagent, Eu(fod)$_3$, Experiments

These experiments have been carried out in deuterochloroform at 30°C in a Bruker AC200 instrument. For each compound, seven or eight points have been determined. Classical least squares procedure has been used to calculate the slopes ($r^2 \geqslant 0.998$). Most significant parameters are presented in Table 10.

Table 10. Eu(fod)$_3$ experiments (chemical shifts in Hz at 200 MHz)

Compound	[S]	L/S	H3		H4		H5		CH_n	
(4)	0.120	0	1499.5	0	1249.7	0	1472.1	0	784.5	0
		0.264[a]	2523.6	1024.1	1620.7	371.0	1866.2	394.1	1688.0	903.5
	Regression									
		Intercept	-22.6		-8.3		-7.9		-7.7	
		Slope	3973.0 (100)		1427.2 (35.9)		1518.0 (38.2)		3477.1 (87.5)	
(1)	0.041	0	1510.4	0	1259.3	0	1531.7	0	1261.8	0
		0.639[a]	1641.8	131.0	1554.2	294.9	2121.0	589.2	2823.5	1561.7
	Regression									
		Intercept	-0.7		-2.0		-3.9		-2.2	
		Slope	204.6 (8.3)		463.0 (18.9)		925.8 (37.7)		2455.9 (100)	
(2)	0.093	0	2303.6	0	1912.5	0	2274.5	0	2530.9	0
		0.857[a]	2979.9	676.3	2358.3	445.7	3179.3	904.8	6135.1	3604.2
	Regression									
		Intercept	2.1		3.0		5.8		1.0	
		Slope	792.9 (18.6)		526.2 (12.4)		1064.9 (25.0)		4255.0 (100)	
(3)	0.038	0	1554.2	0	1283.2	0	1516.0	0		
		0.779[a]	2191.2	637.0	1458.4	175.2	2049.4	533.4		
	Regression									
		Intercept	-6.9		-1.5		-2.7			
		Slope	824.9 (100)		228.5 (22.7)		693.5 (84.1)			

[a] For larger L/S ratios a downward curvature is observed.

Dipole Moment Measurements

All solutions were prepared by weight and preserved under nitrogen atmosphere. Benzene and cyclohexane, Carlo Erba RPE, were dried over 4 A molecular sieves. Dielectric measurements were carried out on a WTW model DK-06 Multidekameter at a frequency of 2.0 MHz. The cell used was made of silvered Pyrex glass and was calibrated at the working temperature of 25.00 ± 0.01°C, using liquids with well known dielectric constant, *i.e.* benzene and cyclohexane. Refractometry. The difference in the refractive index between the solutions and the pure solvent was measured at 546 nm in a Brice-Phoenix 2000V differential refractometer, previously calibrated with aqueous KCl. Densimetry. The specific volumes of the solutions and solvent were determined on an Anton Paar DMA 55 digital densimeter with distilled water and air as calibrating substances.

Computational Details

Theoretical calculations were performed in a Vax-8800 computer in the Universidad Autónoma de Barcelona. Compounds 2 and 3 were not totally optimized (dihedral angles regarding pyrazole rings were fixed).

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