

Synthesis and Structure of *trans*-Dichloro-tetra(pyrazole)-gallium(III) Chloride and Tetrachlorogallate(III)

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[$\text{GaCl}_2(\text{pyrazole})_4]^+\text{Cl}^-$ and [$\text{GaCl}_2(\text{pyrazole})_4]^+\text{GaCl}_4^-$ are formed in the reaction of pyrazole and anhydrous gallium trichloride in toluene/diethyl ether. The crystal structure of the chloride salt shows cations in a *trans*-conformation which are associated with the chloride counterions through N-H-Cl hydrogen bonds.

There is current interest in the bioinorganic chemistry of gallium owing to the extensive use of the element in medicine both as a therapeutic and diagnostic agent [1]. After numerous studies of simple gallium(III) salts [2, 3] recent investigations have focussed on coordination compounds of gallium halides with bio-relevant ligands including also many of the common nitrogen heterocycles [3, 4]. These complexes show high water solubility in the near-physiological pH range and good carrier properties for gallium. Among these nitrogen heterocycles, pyrazole has attracted special attention because of its versatile donor properties for the alkaline earth and earth metals of groups II and XIII.

Surprisingly, in the previous studies only a pyrazole complex of GaCl_3 with a 2:1 ligand-to-metal ratio has been isolated [4]. This deficit of pyrazole ligands leads to a ligand distribution $[\text{GaCl}_2(\text{pyrazole})_4]^+[\text{GaCl}_4]^-$ (**1**) with a tetrachlorogallate(III) counterion. However, the anion is susceptible to hydrolysis giving rise to galenic complications and general limitations to applications. In the present work we report the preparation and the determination of the structure of the complex obtained from reactions with an excess of pyrazole. The product has the stoichiometry $[\text{GaCl}_2(\text{pyrazole})_4]^+\text{Cl}^-$ (**2**), and its crystals are free of solvate molecules. The tetrachlorogallate(III) salt $[\text{GaCl}_2(\text{pyrazole})_4]^+\text{GaCl}_4^-$ (**1**) was also obtained as single crystals and its structure determined.

Treatment of a solution of anhydrous GaCl_3 in diethyl ether with a solution of five equivalents of

dry pyrazole in dry toluene gives a clear, homogeneous reaction mixture, from which a colourless crystalline product separates on cooling to 0 °C. The first crystallise and a second crop recovered from the mother liquor after partial evaporation of solvent contained crystals of the known tetrachlorogallate(III) salt (**1**) together with crystals of the new chloride salt (**2**), which were separated mechanically and subjected to structural studies. Elemental analysis of the bulk material showed that a 1:1 mixture of the components was present. Prolonged heating of this mixture (**1**, **2**) with an even larger excess of pyrazole (4 d in refluxing diethyl ether) gave **2** as the sole product.

Both products (**1**, **2**) are soluble in dichloromethane, chloroform, tetrahydrofuran and also in methanol, ethanol and water.

The NMR spectra of both compounds in CD_2Cl_2 consistently show the resonances of the pyrazole protons in the cations at 6.48 (CH, 1H), 8.05 (CH, 2H) and 10.44 ppm (NH, 1H) with no discernible coupling. The values for free pyrazole are 6.10, 7.74 and 13.60 ppm with $^3J(\text{H},\text{H}) = 2.1$ Hz (in CCl_4). Two carbon signals appear at 106.9 and 135.5 ppm and are thus shifted only slightly with respect to the resonances of the free ligand (104.8 and 133.6 ppm, in CDCl_3). This pattern of signals suggests virtual local C_{2v} symmetry for the ligands in the complex, but there is significant line broadening of the resonances for the CH groups neighbouring the nitrogen atoms, which is partly due to quadrupole interactions, but also suggests some exchange processes in solution.

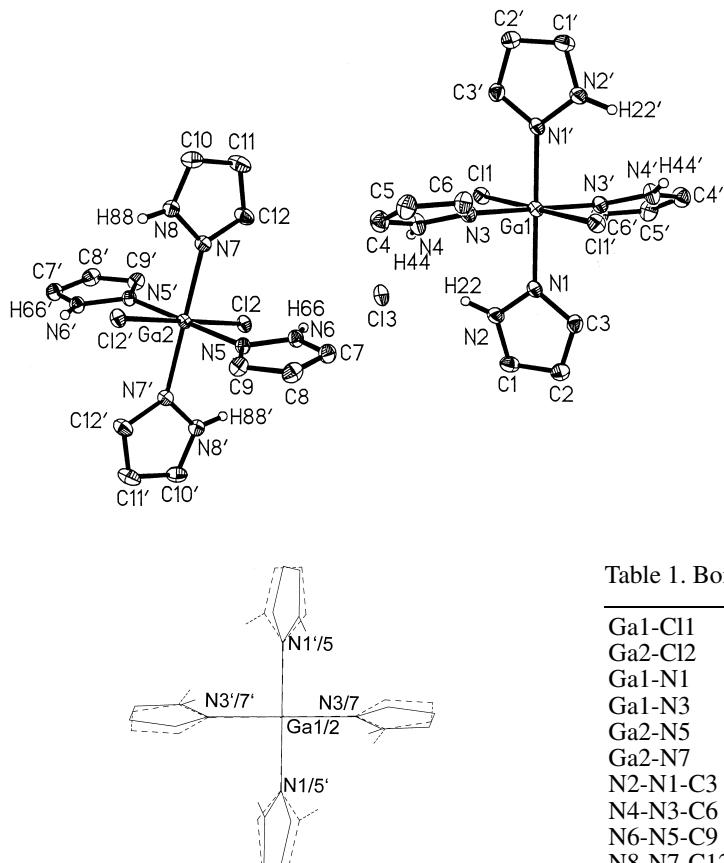


Fig. 1. Top: Structure of the two independent cations and their Cl^- counterion of compound **2** with atomic numbering (ORTEP, 50% probability ellipsoids, C-H atoms omitted). Ligands in *trans* position are related by an inversion center at the gallium positions; bottom: superposition of the two cations illustrating the different dihedral angles between the pyrazole ligands.

Table 1. Bond lengths [\AA] and angles [$^\circ$] of complex **2**.

Ga1-C11	2.3095(5)	N1-N2	1.352(2)
Ga2-Cl2	2.3208(4)	N3-N4	1.354(2)
Ga1-N1	2.087(2)	N5-N6	1.354(2)
Ga1-N3	2.078(2)	N7-N8	1.354(2)
Ga2-N5	2.078(2)	N1-Ga1-N3	91.86(6)
Ga2-N7	2.078(2)	Cl1-Ga1-N1	90.84(5)
N2-N1-C3	105.3(2)	Cl1-Ga1-N3	89.37(5)
N4-N3-C6	105.6(2)	N5-Ga2-N7	90.67(6)
N6-N5-C9	105.5(2)	Cl2-Ga2-N5	89.46(5)
N8-N7-C12	105.5(2)	Cl2-Ga2-N7	90.68(4)
N2-H22	0.88(3)	N2-H22···Cl3	158.7(3)
N4-H44	0.92(4)	N4-H44···Cl3	149.5(3)
N6-H66	0.86(3)	N6-H66···Cl3	136.8(3)
N8-H88	0.85(3)	N8B-H88B···Cl3	128.7(3)
Cl3···H22	2.27(3)	N2···Cl3	3.106(2)
Cl3···H44	2.38(3)	N4···Cl3	3.204(2)
Cl3···H66	2.53(3)	N6···Cl3	3.212(2)
Cl3···H88B ^a	2.75(3)	N8B···Cl3	3.350(2)

^a Symmetry positions of atoms N8B/H88B: $x+1, y+1, z$.

Note that non-fluxional coordination of the metal to only one of the two nitrogen atoms should induce non-equivalence of *all three* CH groups, while rapid site exchange of coordination would render the two CH units next to the nitrogen atoms equivalent. This process must involve an exchange of gallium and hydrogen atoms at the two nitrogen atoms.

The IR spectrum of the product **2** (in KBr) has prominent bands at 3346.2 and 3130.8 cm^{-1} matching almost exactly those published for the tetrachlorogallate(III) analogue (**1**): 3346 $\nu(\text{N-H})$ and 3143 $\nu(\text{C-H}) \text{ cm}^{-1}$ with the same cation. These results are different from the spectral data for free (neat) pyrazole, where strong N-H- \cdots N hydrogen bonding leads to shifts and to broadening of the N-H bands. It may therefore be concluded that in solid **1** and **2** the pyrazole molecules are fixed in positions where inter-ligand N-H- \cdots N hydrogen bonds cannot be maintained.

Crystals of compound **2** are triclinic, space group $P\bar{1}$, with $Z=2$ independent formula units in the unit

cell. The asymmetric unit thus contains one half of each of the two formula units with the gallium atoms residing on centers of inversion. The two cations have very similar structures as shown in a diagram of the superimposed units (Fig. 1). As required by symmetry, in both cations the chlorine ligands are in axial positions (*trans*) at the gallium atoms which are in an octahedral GaCl_2N_4 environment. Four pyrazole ligands occupy the equatorial positions and are attached to the gallium atom through only one nitrogen atom.

The Ga-Cl bond lengths are 2.3095(5) and 2.3208(4) \AA , the Ga-N distances in the range

Table 2. Bond lengths [\AA] and angles [$^\circ$] in the cations of complex **1**.

Ga1-Cl1	2.3434(4)	N1-N2	1.351(3)
Ga2-Cl2	2.3396(4)	N3-N4	1.348(2)
Ga1-N1	2.078(2)	N5-N6	1.351(2)
Ga1-N3	2.078(2)	N7-N8	1.354(2)
Ga2-N5	2.086(2)	N1-Ga1-N3	90.37(7)
Ga2-N7	2.070(2)	Cl1-Ga1-N1	89.82(5)
N2-N1-C1	105.5(2)	Cl1-Ga1-N3	90.31(4)
N4-N3-C4	104.7(2)	N5-Ga2-N7	91.53(6)
N6-N5-C7	105.6(2)	Cl2-Ga2-N5	90.21(5)
N8-N7-C10	105.7(2)	Cl2-Ga2-N7	90.02(4)

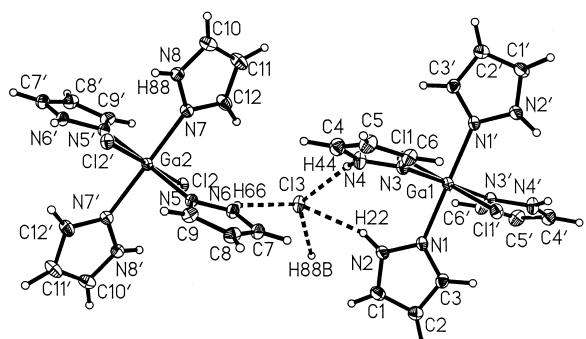


Fig. 2. Hydrogen bonding between the Cl^- anion and three cations in **2**. (The third cation is only represented by H88B).

2.078(2) - 2.087(2) \AA (Table 1), and these data are in good agreement with reference values [4]. Deviations of the angles at gallium from 90° are

less than 2° . The free chloride anions have contacts with four N-H groups of three different cations with distances which suggest weak N-H- \cdot Cl hydrogen bonding (Fig. 2). The individual data are listed in Table 1. All pyrazole ligands are virtually planar and form different torsional angles relative to their neighbouring congeners as already shown in the superposition presented in Fig. 1 (bottom). It appears that rotation of the ligands has a flat energy profile allowing packing forces (hydrogen bonds) to influence the conformation of the cations.

Crystals of compound **1** are triclinic, space group $P\bar{1}$ with $Z = 2$ formula units in the unit cell. As also found for **2**, the asymmetric unit contains one half of each of two independent cations, and one tetrachlorogallate(III) anion. The remainder of the cations are generated through inversion symmetry (Figure 3). The geometrical details of the cations are very similar to those described for **2** and need no further discussion. The N-H- \cdot Cl contacts in the structure suggest weak hydrogen bonding, but there are no unusual connectivities.

Experimental Section

The experiments were carried out under pure, dry nitrogen. Solvents were dried and saturated with nitrogen, and glassware was oven-dried and filled with nitrogen. Standard equipment was used throughout. All chemicals were reagent grade.

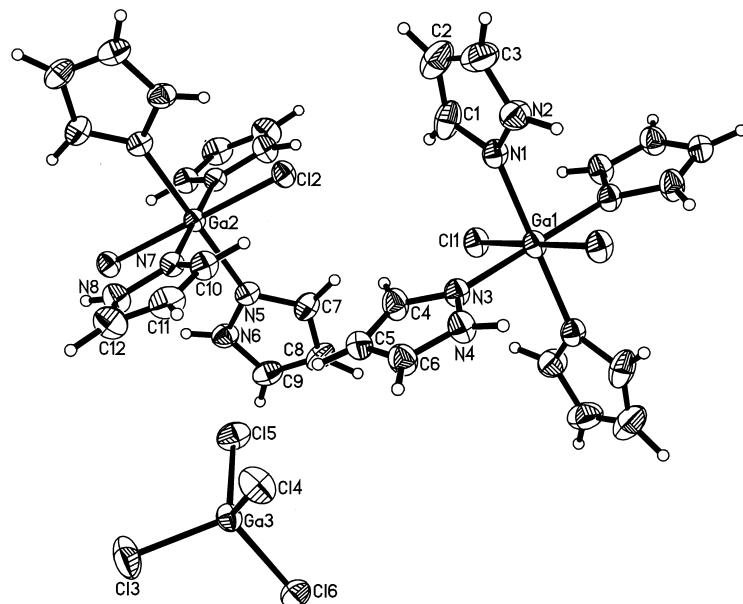


Fig. 3. Structure of the two independent cations $[\text{GaCl}_2(\text{pyrazole})_4]^+$ and their $[\text{GaCl}_4]^-$ counterion in complex **1**.

trans-Dichloro-tetra(pyrazole)gallium(III) chloride (**2**) and tetrachlorogallate(III) (**1**)

Pyrazole (3.008 g, 44.17 mmol) was dissolved in toluene (100 ml) and this solution was added to a solution of gallium trichloride (1.496 g, 8.496 mmol) in diethyl ether (20 ml). The mixture was heated to reflux for 2 h and then cooled to 0 °C over night. A colourless precipitate separated which was filtered off, washed with small portions of toluene and diethyl ether and dried *in vacuo* (yield 2.1 g, 55%). ¹H NMR (CD₂Cl₂, 20 °C): 6.48 ppm (s, 1H, CH), 8.05 (s, 2H, NCH), 10.44 (br. s, 1H, NH). ¹³C{¹H} NMR (CD₂Cl₂, 20 °C): 106.8 (s, CH), 135.5 (s, NCH). IR (KBr) [cm⁻¹]: 3346, 3130, 1515, 1470, 1480, 1351, 1288, 1150, 1054, 1064, 947, 908, 791, 767, 699, 683. Elemental analysis was carried out for two crops of crystals (first crystallisate, and second crystallisate from the mother liquor) and showed consistently that a 1:1 mixture of **1** and **2** was present: C₁₂H₁₆N₈Ga_{1.5}Cl_{4.5} calcd. C 26.87, H 3.01, N 20.88, Cl 29.74; found C 26.87 / 26.62, H 3.03 / 3.03, N 21.07 / 20.64, Cl 30.41. Prolonged heating of this product mixture in refluxing diethyl ether (4 d) gave a crop of crystals which analyzed as almost pure **2**. C₁₂H₁₆N₈GaCl₃ (448.40) calcd. C 32.14, H 3.60, N 24.99, Cl 23.72; found C 31.87, H 3.60, N 24.59, Cl 24.82. For elemental analysis data for **1** see ref. [4].

Crystal structure determinations

The crystalline samples were placed in inert oil, mounted on a glass pin, and transferred to the cold gas stream of the diffractometer. Crystal data were collected and integrated using a Nonius DIP2020 system with monochromated Mo-K_α ($\lambda = 0.71073 \text{ \AA}$) radiation. The

structures were solved by direct methods using SHELXS-97 and refined by full matrix least-squares calculations on F^2 using SHELXL-97. Non-hydrogen atoms were refined with anisotropic thermal parameters. All hydrogen atoms were located and refined with isotropic contributions.

Crystal data for C₁₂H₁₆Cl₃GaN₈: $M = 448.40$, 0.40 $\times 0.20 \times 0.15 \text{ mm}^{-3}$, triclinic, space group $P\bar{1}$, $Z = 2$, $a = 7.9654(1)$, $b = 8.4210(1)$, $c = 14.7752(3) \text{ \AA}$, $\alpha = 103.002(1)^\circ$, $\beta = 90.474(1)^\circ$, $\gamma = 111.215(1)^\circ$, $V = 895.82(2) \text{ \AA}^3$, $d_{\text{calc}} = 1.662 \text{ g cm}^{-3}$; $F(000) = 452$, $T = 143(2) \text{ K}$; 41596 measured and 5455 unique data ($R_{\text{int}} = 0.031$); 284 refined parameters, $wR2 = 0.0962$, $R1 = 0.0381$ [$I \geq \sigma(I)$]; residual electron densities: 0.560 / -0.954 e \AA^{-3} . The function minimized was $wR2 = \{[\sum w(F_o^2 - F_c^2)^2] / \sum [w(F_o^2)^2]\}^{1/2}$; $w = 1/[\sigma^2(F_o^2) + (ap)^2 + bp]$; $p = (F_o^2 + 2F_c^2)/3$; $a = 0.0506$, $b = 1.04$.

Crystal data for C₁₂H₁₆Cl₆Ga₂N₈: $M = 624.47$, 0.40 $\times 0.30 \times 0.30 \text{ mm}^{-3}$, triclinic, space group $P\bar{1}$, $Z = 2$, $a = 8.8070(1)$, $b = 8.8210(1)$, $c = 15.1450(2) \text{ \AA}$, $\alpha = 103.946(1)^\circ$, $\gamma = 94.226(1)^\circ$, $\gamma = 90.312(1)^\circ$, $V = 1138.45(2) \text{ \AA}^3$, $d_{\text{calc}} = 1.822 \text{ g cm}^{-3}$; $F(000) = 616$, $T = 143(2) \text{ K}$; 44692 measured and 7093 unique data ($R_{\text{int}} = 0.026$); 230 refined parameters, $wR2 = 0.1066$, $R1 = 0.0424$ [$I \geq \sigma(I)$]; residual electron densities: 0.762 / -1.324 e \AA^{-3} . The function minimized was $wR2 = \{[\sum w(F_o^2 - F_c^2)^2] / \sum [w(F_o^2)^2]\}^{1/2}$; $w = 1/[\sigma^2(F_o^2) + (ap)^2 + bp]$; $p = (F_o^2 + 2F_c^2)/3$; $a = 0.0639$, $b = 0.46$. Important interatomic distances and angles are shown in the Tables. Anisotropic displacement parameters and tables of interatomic distances and angles have been deposited with the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK. The data are available on request on quoting CCDS-171190 and 172738.

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