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Observation of a Direct Interaction between the Carbonyl Oxygen, O(6), of a N(7)-Bonded 6-Oxopurine and a Metal Center. Preparation and Crystal and Molecular Structure of (*N*-3,4-Benzosalicylidene-*N'*,*N'*-dimethylethylenediamine)-(theophyllinato)copper(II) Monohydrate

David J. Szalda, Thomas J. Kistenmacher,* and Luigi G. Marzilli*

Contribution from the Department of Chemistry, The Johns Hopkins University, Baltimore, Maryland 21218. Received June 7, 1976

Abstract: The preparation and crystal and molecular structure of the complex (*N*-3,4-benzosalicylidene-*N'*,*N'*-dimethylethylenediamine)(theophyllinato)copper(II) are reported. The complex crystallizes, as the monohydrate, from the reaction mixture with 95% ethanol as the solvent. The crystals are monoclinic, space group *Pc*, with $a = 10.689$ (2), $b = 6.925$ (3), $c = 15.463$ (4) Å, $\beta = 100.27$ (2)°, $Z = 2$, $V = 1126.2$ Å³, $d_{\text{measd}} = 1.50$ (2) g cm⁻³, $d_{\text{calcd}} = 1.48$ g cm⁻³. The 7359 reflections in the $+h$ hemisphere to $2\theta = 60^\circ$ were collected by counter methods on an automated diffractometer, employing crystal-monochromated MoK α radiation and the θ - 2θ scan technique. The 7359 measured reflections were subsequently reduced to a symmetry independent set of 3138 intensities, which were used in the structural solution and refinement. Standard heavy-atom Patterson and Fourier methods were used to solve the structure, and refinement by full-matrix least squares, based on F , has led to a final R value of 0.037. The coordination geometry about the copper(II) is (4 + 1) with the equatorial positions occupied by the tridentate Schiff base chelate and N(7) of the theophylline monoanion, Cu-N(7) bond length = 1.956 (3) Å, and one of the axial positions is occupied by the carbonyl oxygen at C(6) of the purine ring system, Cu-O(6) distance = 2.919 (3) Å. This represents the first observation of a significant, direct interaction between the carbonyl oxygen of a 6-oxopurine and a metal center. The complexes are connected along the a axis by an O(10)(Schiff base) . . . H-O-H . . . O(2)(theophylline monoanion) hydrogen bond system involving translationally related complexes. Further crystal stability is obtained by a "pinning" of the naphthylidene rings of the Schiff base chelate by methyl groups from the ethylenediamine terminus and the theophylline monoanion ring.

Investigations into the binding of metal ions and metal complexes to nucleic acids and their constituents, both in solution¹ and in the solid state,² have recently been summarized. Activity in this area has been stimulated by both the importance of such interactions in living systems, and also the potential importance of metal binding in the functioning of platinum(II) cancer chemotherapeutics.

Chelation of metal centers by N(7) and either the 6-oxo or 6-amino exocyclic groups of purines has been widely suggested on the basis of a number of spectroscopic and physical criteria.³ Such chelate formation has been a major theme in the early literature and has been continually suggested despite numerous recent solution¹ and x-ray structural² investigations, which have failed to provide direct evidence for such a mode of binding. Rather, it has become clear that whereas N(7) of the five-membered imidazole ring of purines forms a strong bond to the metal, the exocyclic oxo or amino groups engage in hydrogen bonding to other ligands attached to the metal.² No direct bond has been found between the common exocyclic groups of the purines and the metal center.

Some insight into the chelation mode of binding has been derived from structural studies on 6-thiopurines. In bis(6-

mercapto-9-benzylpurine)palladium(II),^{4,5} the palladium(II) is complexed to both N(7), Pd(II)-N(7) bond lengths of 2.05 (1) and 2.08 (1) Å for the two independent ligands, and S(6), Pd(II)-S(6) bond lengths of 2.305 (3) and 2.311 (3) Å. All these bond lengths are normal for Pd(II) chelate systems.^{2,4,5} A second example of 6-thiopurine chelation has been found in the complex bis[dichloro(6-mercapto-9-methylpurine)copper(II)].⁶ In this complex, however, the Cu(II)-N(7) bond length, 1.992 (4) Å, is normal, while the Cu(II)-S(6) bond length, 2.424 (1) Å, is about 0.2-0.4 Å longer than expected.⁶

The absence of chelation in 6-oxopurines, but the presence of such chelate formation in 6-thiopurines, has been rationalized on the basis of geometric⁷ and coordination affinity grounds.²

We have investigated a metal-chelate ligand system which precludes interligand hydrogen bonding to the exocyclic oxo group, but nevertheless presents a vacant coordination site for direct binding between the exocyclic oxygen and the metal center. The system selected contains Cu(II) chelated by the mononegative, tridentate Schiff base ligand *N*-3,4-benzosalicylidene-*N'*,*N'*-dimethylethylenediamine. In this system, the

Table I. Crystal Data for [(*N*-3,4-Benzosalicylidene-*N'*,*N'*-dimethylethylenediamine)(theophyllinato)copper(II)] Monohydrate

$a = 10.689 (2) \text{ \AA}$	$\text{Cu}(\text{O}_3\text{N}_6\text{C}_{22}\text{H}_{24}) \cdot \text{H}_2\text{O}$
$b = 6.925 (3)$	mol wt = 502.0
$c = 15.463 (4)$	$d_m = 150 (2) \text{ g cm}^{-3}$
$\beta = 100.27 (2)^\circ$	$d_c = 1.48 \text{ g cm}^{-3}$
$V = 1126.2 \text{ \AA}^3$	Space group: <i>Pc</i>
$Z = 2$	$\mu = 10.6 \text{ cm}^{-1}$
$\lambda(\text{MoK}\alpha) = 0.71069 \text{ \AA}$	

tridentate ligand cannot donate a hydrogen bond and the methyl groups discourage the coordination of a water molecule (an alternative hydrogen bond donor to O(6)) to the axial coordination positions. However, an equatorial coordination position is available for binding to purine or pyrimidine ligands, and we have prepared and studied a complex in which the theophylline monoanion, where theophylline is 1,3-dimethyl-2,6-dioxopurine, is bonded to this equatorial position through N(7). A direct, albeit weak, bond is formed between the exocyclic oxygen O(6) and the copper(II) center. This complex allows the first evaluation of the bonding in such a chelate utilizing the common 6-oxo grouping.

Experimental Section

Preparation of (*N*-3,4-Benzosalicylidene-*N'*,*N'*-dimethylethylenediamine)(theophyllinato)copper(II) Monohydrate. The starting complex (chloro) (*N*-3,4-benzosalicylidene-*N'*,*N'*-dimethylethylenediamine)copper(II) was prepared by a modification of the method of Sacconi and Bertini.⁸ The addition of AgNO_3 (0.16 g, 1 mmol) to a solution of the starting chloro complex (0.36 g, 1 mmol) in 95% ethanol (40 ml) resulted in the precipitation of AgCl . The solution was then filtered, and theophylline (0.18 g, 1 mmol) and KOH (0.06 g, 1 mmol) were added to the filtrate. Slow evaporation of the solvent resulted in the formation of deep-violet crystals of the theophylline monoanion complex. The magnetic moment, determined by the Faraday method on a polycrystalline sample, has a value of $1.9 \mu_B$, which is typical of tridentate Schiff base complexes of copper(II).

Collection and Reduction of the X-Ray Intensity Data. Preliminary oscillation and Weissenberg photographs showed the crystal system to be monoclinic with systematic absences ($h0l, l = 2n + 1$) consistent with the space groups *Pc* and *P2/c*. Unit-cell dimensions and their associated standard deviations were derived from a least-squares fit to the 2θ , ω and χ setting angles for 15 carefully centered reflections. The crystal density, measured by the neutral buoyancy technique in carbon tetrachloride/cyclohexane, indicated two complexes and two water molecules per unit cell. The presence of two complexes per unit cell is most readily consistent with the space group *Pc*, as the complexes would be required to have incommensurate twofold symmetry in space group, *P2/c*. Complete crystal data are collected in Table I.

The intensities of 7359 reflections (the $+h$ hemisphere to $2\theta = 60^\circ$, $\lambda(\text{Mo K}\alpha) = 0.71069 \text{ \AA}$) were measured on a Syntex P-1 automated diffractometer, employing graphite-monochromatized radiation. The crystal used in data collection was a multifaceted, capped prism with well-developed $\{010\}$ [0.25 mm] and $\{001\}$ [0.25 mm] forms and minor development of the forms $\{00\}$, $\{101\}$, and $\{110\}$. The overall length of the specimen was 0.34 mm. The a^* axis was mounted about 13° off the ϕ axis of the diffractometer. Intensity data were collected in the θ - 2θ scan mode with individual scan speeds (2 – $24^\circ \text{ min}^{-1}$) determined from a rapid scan at the calculated Bragg peak. The intensities of three standards were monitored after every 100 reflections and showed no systematic variation over the course of the data collection (maximum deviation of any standard from its mean value of about 3%). The 7359 measured intensities (which included standards, systematic absences, and a full set of symmetry-related data) were then reduced to a set of 3138 symmetry-independent reflections. All reflections were assigned observational variances based on the equation

$$\sigma^2(I) = S + (B_1 + B_2)(T_S/2T_B)^2 + (pI)^2$$

where S , B_1 , and B_2 are the scan and extremum background counts, T_S and T_B are the scan and individual background counting times (T_B

$= 1/4T_S$ for all reflections), and p was taken to be 0.04 and represents the expected error proportional to the diffracted intensity⁹ as determined by the random variation in the intensity of the standards. The intensities and their standard deviations were corrected for Lorentz and polarization effects, but no correction for absorption was deemed necessary ($\mu = 10.6 \text{ cm}^{-1}$). The amplitudes of reflections with negative intensities were set equal to zero. An approximate absolute scale was determined by the method of Wilson.¹⁰

Solution and Refinement of the Structure. As noted above, our choice for the space group was *Pc* based on molecular symmetry considerations. The Cu was used to determine the origin, and its y coordinate was deduced from the $P(0, 2v, 1/2)$ Harker line. Two cycles of structure factor-Fourier calculations allowed the positioning of the remaining 32 nonhydrogen atoms in the asymmetric unit (including all the nonhydrogen atoms, $R = \sum ||F_o| - |F_c|| / \sum |F_o| = 0.26$). Four cycles of full-matrix, isotropic least squares, minimizing the quantity $\sum w(|F_o| - |F_c|)^2$, where $w = 4F_o^2/\sigma^2(F_o^2)$, reduced the R value to 0.074. A difference Fourier was computed at this stage and the 26 hydrogen atoms in the asymmetric unit positioned. The temperature factors of the hydrogen atoms were set equal to $1.5 \text{ \AA}^2 + B$ of the heavy atom to which they were bonded. Four further cycles of refinement, employing anisotropic thermal parameters for the nonhydrogen atoms and holding the hydrogen atom parameters fixed, led to convergence and a final R value of 0.037. The final weighted R value [$R_w = (\sum w(|F_o| - |F_c|)^2 / \sum w|F_o|^2)^{1/2}$] and goodness-of-fit [$(\sum w(|F_o| - |F_c|)^2 / (\text{NO} - \text{NV}))^{1/2}$, where $\text{NO} = 3138$ observations and $\text{NV} = 293$ variables] were 0.038 and 1.5, respectively.

Neutral scattering factor curves for all nonhydrogen atoms were taken from the compilation of Hanson, Herman, Lea, and Skillman,¹¹ while the scattering curve for H was that of Stewart, Davidson, and Simpson.¹² The real part of the scattering curve for Cu was corrected for anomalous dispersion effects.¹³ Final nonhydrogen atom parameters are collected in Table II; hydrogen atom parameters are given in Table III. A complete list of calculated and observed structure factor amplitudes is available.¹⁴

The structure factor and Fourier calculations were done using the X-RAY 67 series of programs,¹⁵ least-squares refinement were done using an extensively modified version of ORFLS,¹⁶ best planes were computed with the program of Pippy and Ahmed,¹⁷ and the illustrations were prepared with the aid of ORTEP.¹⁸ All other calculations were performed with locally written programs.

Results and Discussion

The molecular conformation of (*N*-3,4-benzosalicylidene-*N'*,*N'*-dimethylethylenediamine)(theophyllinato)copper(II) is illustrated in Figure 1. The primary coordination sphere is pseudo-square pyramidal with the tridentate Schiff base and N(7) of the theophylline monoanion, $\text{Cu-N}(7) = 1.956 (3) \text{ \AA}$, defining the equatorial plane and O(6) of the pyrimidine ring of the coordinated monoanion occupying one of the axial positions, $\text{Cu-O}(6) = 2.919 (3) \text{ \AA}$. The theophylline monoanion acts, then, as a chelated ligand employing one of the equatorial and one of the axial ligating positions. This is the first instance where chelation by a 6-oxopurine, albeit weak, has been observed.

The factors leading to the chelation of the theophylline monoanion appear to be the following. (1) We have noted in several instances now that the theophylline monoanion usually partakes in interligand hydrogen bonding with suitable donors on other ligands in the coordination sphere.¹⁹ In particular, the theophylline monoanion complex of (*N*-salicylidene-*N'*-methylthylenediamine)copper(II)²⁰ and the monomethyl analogue of the present complex²¹ show NH(ethylenediamine) . . . O(6) interligand hydrogen bonds. The absence of any coordinated potential hydrogen bond donor on the Schiff base in the present complex precludes the formation of an interligand hydrogen bond to O(6). (2) In several Cu(II)-6-oxopurine complexes, coordinated water molecules in axial or equatorial positions have been employed in interligand hydrogen bonding to O(6).^{7,21-24} As we have noted previously, however, the presence of the axial methyl group at the *N*-methylthylenediamine terminus of the methylated Schiff bases appears to preclude strong on-axis coordination at one

Table II. Final Nonhydrogen Atom Parameters ($\times 10^4$)^a

Atom	x	y	z	B ₁₁	B ₂₂	B ₃₃	B ₁₂	B ₁₃	B ₂₃
Cu	0	932 (0.5)	0	53 (0.2)	149 (0.6)	26 (0.1)	-4 (0.5)	11 (0.1)	-5 (0.4)
O(2)	-4849 (3)	1138 (4)	2074 (2)	87 (3)	295 (8)	69 (2)	-34 (4)	36 (2)	-2 (3)
O(6)	-2090 (3)	-1707 (4)	125 (2)	117 (3)	230 (6)	51 (1)	-18 (4)	25 (2)	-44 (3)
O(10)	1093 (2)	-805 (3)	767 (1)	86 (2)	203 (5)	27 (1)	24 (3)	12 (1)	1 (2)
O(31)	2817 (3)	644 (4)	2231 (2)	107 (3)	231 (6)	39 (1)	1 (3)	13 (1)	-14 (2)
N(1)	-3460 (3)	-1409 (4)	1114 (2)	74 (3)	189 (6)	42 (1)	-23 (3)	12 (1)	-9 (2)
N(3)	-3356 (3)	1214 (4)	2107 (2)	62 (2)	204 (7)	38 (1)	3 (3)	19 (1)	-7 (2)
N(7)	-792 (3)	1847 (4)	971 (2)	64 (2)	194 (7)	34 (1)	-15 (3)	16 (1)	-11 (2)
N(9)	-1596 (3)	3426 (5)	2038 (2)	92 (3)	211 (7)	42 (1)	-35 (4)	25 (2)	-35 (3)
N(17)	823 (3)	193 (4)	-971 (2)	70 (2)	178 (6)	28 (1)	9 (3)	15 (1)	6 (2)
N(20)	-1079 (2)	2735 (4)	-906 (2)	64 (2)	160 (6)	34 (1)	7 (3)	8 (1)	-1 (2)
C(1)	-4115 (5)	-3180 (7)	769 (3)	124 (5)	243 (11)	74 (3)	-85 (6)	27 (3)	-47 (5)
C(2)	-3934 (3)	-474 (5)	1785 (2)	60 (3)	211 (8)	40 (1)	-4 (4)	11 (2)	3 (3)
C(3)	-3850 (4)	2287 (7)	2776 (3)	109 (4)	292 (11)	50 (2)	4 (6)	40 (2)	-25 (4)
C(4)	-2289 (3)	1851 (5)	1790 (2)	62 (3)	172 (7)	29 (1)	2 (4)	11 (1)	-1 (2)
C(5)	-1830 (3)	861 (5)	1147 (2)	54 (2)	157 (6)	31 (1)	2 (3)	11 (1)	-3 (2)
C(6)	-2412 (3)	-843 (5)	741 (2)	68 (3)	161 (7)	36 (1)	-8 (4)	12 (2)	-6 (3)
C(8)	-711 (4)	3350 (6)	1522 (2)	93 (4)	212 (8)	43 (2)	-52 (5)	24 (2)	-29 (3)
C(10)	1739 (3)	-2286 (5)	540 (2)	54 (2)	180 (7)	28 (1)	-3 (3)	8 (1)	3 (2)
C(11)	2122 (3)	-3702 (5)	1194 (2)	80 (3)	173 (7)	28 (1)	-7 (4)	13 (2)	10 (2)
C(12)	2749 (4)	-5334 (5)	1023 (2)	84 (3)	180 (7)	35 (1)	-9 (4)	6 (2)	16 (3)
C(13)	3096 (3)	-5636 (4)	177 (2)	65 (3)	149 (7)	40 (1)	-14 (3)	7 (1)	-4 (2)
C(14)	2795 (3)	-4224 (4)	-476 (2)	52 (2)	151 (6)	34 (1)	-14 (3)	6 (1)	-5 (2)
C(15)	2063 (3)	-2520 (5)	-297 (2)	53 (2)	147 (6)	28 (1)	-8 (3)	10 (1)	-1 (2)
C(16)	1615 (3)	-1197 (5)	-999 (2)	63 (3)	187 (7)	26 (1)	-1 (3)	15 (1)	0 (2)
C(18)	436 (4)	1400 (6)	-1759 (2)	112 (4)	242 (9)	30 (1)	44 (5)	21 (2)	20 (3)
C(19)	-923 (4)	1974 (6)	-1774 (2)	97 (4)	197 (8)	35 (1)	13 (5)	3 (2)	1 (3)
C(20)	-2466 (4)	2767 (7)	-869 (3)	65 (3)	319 (12)	68 (2)	19 (5)	4 (2)	23 (5)
C(21)	3769 (4)	-7342 (5)	19 (3)	86 (3)	161 (7)	54 (2)	10 (4)	8 (2)	4 (3)
C(22)	4148 (4)	-7589 (6)	-766 (3)	87 (4)	211 (9)	67 (2)	29 (5)	17 (2)	-18 (4)
C(23)	3882 (4)	-6176 (6)	-1423 (3)	94 (4)	234 (9)	47 (2)	23 (5)	22 (2)	-19 (3)
C(24)	3215 (3)	-4532 (5)	-1281 (2)	77 (3)	203 (8)	37 (1)	12 (4)	12 (2)	-12 (3)
C(26)	-575 (4)	4717 (6)	-761 (3)	121 (5)	177 (8)	56 (2)	-10 (5)	1 (2)	-2 (3)

^a Estimated standard deviations in this table and the following tables are enclosed in parentheses. The form of the anisotropic ellipsoid is: $\exp[-(B_{11}h^2 + B_{22}k^2 + B_{33}l^2 + 2B_{12}hk + 2B_{13}hl + 2B_{23}kl)]$.

Table III. Hydrogen Atom Positional ($\times 10^3$) and Isotropic Thermal Parameters

Atom	x	y	z	B ^a
H(1)[C(1)]	-390	-424	56	7.0
H(2)[C(1)]	-470	-266	25	7.0
H(3)[C(1)]	-461	-351	118	7.0
H(4)[C(3)]	-340	324	312	7.0
H(5)[C(3)]	-460	320	240	7.0
H(6)[C(3)]	-447	189	340	7.0
H(8)[C(8)]	-8	432	155	6.0
H(11)[C(11)]	192	-354	177	5.0
H(12)[C(12)]	297	-631	147	5.0
H(16)[C(16)]	196	-134	-152	4.0
H(17)[C(18)]	53	73	-227	5.0
H(18)[C(18)]	96	254	-171	5.0
H(19)[C(19)]	-146	89	-193	5.0
H(20)[C(19)]	-116	296	-222	5.0
H(21)[C(21)]	396	-831	47	6.0
H(22)[C(22)]	460	-875	-88	6.0
H(23)[C(23)]	415	-638	-197	6.0
H(24)[C(24)]	304	-358	-173	5.0
H(25)[C(20)]	-290	136	-76	7.0
H(26)[C(20)]	-287	315	-145	7.0
H(27)[C(20)]	-275	390	-44	7.0
H(28)[C(26)]	30	469	-52	6.0
H(29)[C(26)]	-101	534	-34	6.0
H(30)[C(26)]	-70	550	-125	6.0
H(31)[O(31)]	357	18	224	6.0
H(32)[O(31)v6]	220	18	170	6.0

^a The hydrogen atom isotropic thermal parameters were set to about 1.5 \AA^2 + the isotropic thermal parameter of the atom to which they are attached [enclosed in brackets].

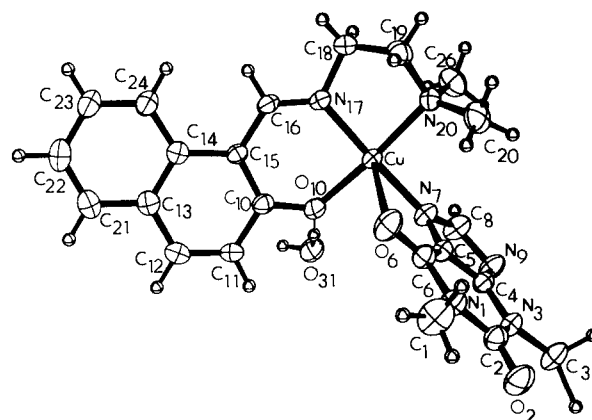


Figure 1. A perspective view of the (*N*-3,4-benzosalicylidene-*N*',*N*'-dimethylethylenediamine)(theophyllinato)copper(II) complex and its associated water of hydration. The thermal ellipsoids are drawn at the 50% probability level.

of the axial positions.^{20,25} Moreover, it is unlikely, for steric reasons, that the pyrimidine ring of the theophylline anion will be on the same side of the equatorial plane as the axial methyl group.²⁵ Space filling models indicate that the equatorial methyl group would provide steric hindrance to a Cu-OH₂...O(6) hydrogen bond system of the type found in the monomethyl analogue.²¹ It appears that the presence of the 6-oxo group near the relatively open axial position of the primary coordination sphere, the absence of interligand hydrogen bond formation, and the blocking of the other axial position by the axial methyl group motivates the formation of the Cu-O(6) bond.

Table IV. Conformational Features about N(7) in Several Cu(II)-N(7)-Bonded 6-Oxopurine Complexes

Complex	Cu-N(7), Å	Cu-N(7)-C(5), deg	Cu-N(7)-C(8), deg	C(5)-N(7)-C(8)	Sum of angles at N(7)	Cu-O(6)	Intramolecular hydrogen bonding
1 ^a	1.986 (1)	138.0 (1)	118.9 (1)	103.0 (3)	359.9	3.730 (1)	N-H(eq)...O(6)
2 ^b	2.000 (3)	136.1 (2)	117.0 (2)	103.1 (3)	356.2	3.739 (3)	N-H(eq)...O(6) OH ₂ (ax)...O(6)
3 ^c	2.007 (3)	135.9 (3)	120.2 (3)	102.9 (3)	359.0	3.683 (3)	N-H(eq)...O(6)
4 ^d	1.956 (3)	117.8 (2)	138.9 (2)	102.9 (3)	359.6	2.919 (3)	None
5 ^e	2.006 (3)	136.5 (2)	118.8 (2)	104.4 (3)	359.7	3.834 (3)	OH ₂ (eq)...O(6)
6 ^f	1.965 (3)	127.9 (2)	127.2 (2)	104.8 (3)	359.9	3.278 (3)	None
7 ^g	2.055 (2)	135.0 (1)	120.2 (1)	104.7 (1)	359.9	3.746 (2)	OH ₂ (eq)...O(6)
7 ^g	2.016 (5)	133.8 (5)	118.8 (5)	104.6 (5)	357.2	3.760 (5)	OH ₂ (ax)...O(6)
7 ^g	2.020 (5)	132.2 (5)	121.0 (5)	104.9 (5)	358.1	3.752 (5)	OH ₂ (ax)...O(6)

^a (*N*-Salicylidene-*N'*-methylethylenediamine)(theophyllinato)copper(II), ref 20. ^b (*N*-3,4-Benzosalicylidene-*N'*-methylethylenediamine)(theophyllinato)(aquo)copper, ref 21. ^c Bis(theophyllinato)(diethylenetriamine)copper(II), ref 27. Only the parameters for the equatorially bound theophylline monoanion are included. ^d This study. ^e [Nitratobis(aquo)bis(theophylline)copper(II)]⁺, ref 22. ^f Dichlorobis(9-methylhypoxanthine)bis(aquo)copper(II), ref 7. ^g [Triaquobis(9-methylguanine)copper(II)]²⁺, ref 24.

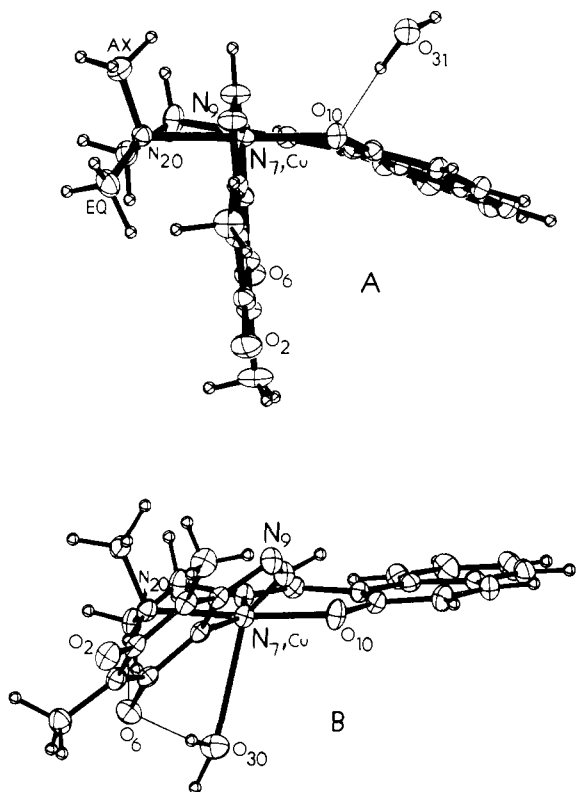


Figure 2. A comparison of the molecular geometries of *N',N'*-dimethyl- (A) and *N'*-methylbenzosalicylidene (B) complexes. In each case the view direction is along the N(7)-Cu bond

The Cu-O(6) bond length, 2.919 (3) Å, is significantly longer than is observed for occupation of the axial position by water or small anions.^{19,22-32} This distance is, however, considerably shorter than the average Cu...O(6) distance of 3.75 (5) Å when O(6) is involved in interligand hydrogen bonding (Table IV) or when there is no intramolecular interaction involving O(6), 3.278 (3) Å (Table IV).

Even acknowledging the apparent weakness of the Cu-O(6) bond, the conformational consequences of its formation are dramatic. Figure 2 compares, for example, the molecular conformations of the complex presented here and its monomethyl analogue,²¹ as viewed down the N(7)-Cu bond. In the monomethyl complex, where interligand hydrogen bonding takes place, the dihedral angle between the purine plane and the equatorial plane is 44.7 (1)°, while the dihedral angle is 85.8 (1)° in this case (see Figure 2). Furthermore, we have

shown that the formation of interligand hydrogen bonds to O(6) causes a dissymmetry in the exocyclic bond angles at N(7)¹⁹ (see Table IV), where Cu-N(7)-C(5) is normally about 133° and Cu-N(7)-C(8) is about 119°. In the present case, however, just the opposite dissymmetry is observed with Cu-N(7)-C(5) = 117.8 (2)° and Cu-N(7)-C(8) = 138.9 (2)°. These two conformational changes bring O(6) about onto the open axial position, as evidenced by the angles involving O(6) in the primary coordination sphere (Table V).

We wish to note further that of the seven 6-oxopurine complexes of Cu(II) reported in Table IV, six show interligand hydrogen bonding, while only in the present case is chelation via N(7) and O(6) observed (a second exception occurs in entry 6 of Table IV, where a second theophylline ligand in the coordination sphere shows no intramolecular interaction involving O(6), and we further note that in the complex bis(theophyllinato)(diethylenetriamine)copper(II), entry 3 of Table IV, an axially-coordinated theophylline monoanion shows no intracomplex interactions via O(6)). In six of the seven complexes listed in Table IV the copper(II) extends its coordination sphere to 4 + 1 or 4 + 2 by an axial interaction with a water molecule or an anion; however, the present case is the only one in which O(6) is used for this purpose and it is the weakest of these axial interactions. These observations would seem to imply that the formation of the interligand hydrogen bond, *where possible*, is more favorable than the formation of the Cu-O(6) bond. This is in sharp contrast to the case of cytidine(cytosine), where the intramolecular Cu-O(2) bond is more favorable than the formation of an intramolecular hydrogen bond.^{19,33-36}

Bond Lengths and Angles. A complete list of intramolecular bond distances and bond angles are contained in Table V. The Cu-N(7) bond length, 1.956 (3) Å, is the shortest yet observed in the binding of a theophylline monoanion to Cu(II) (Table IV). The Cu-N(7) distance is 0.03 Å shorter than that found in the four-coordinate complex of the theophylline anion with (*N*-salicylidene-*N'*-methylethylenediamine)copper(II),²⁰ and 0.04 Å shorter than is observed in the monomethyl analogue²¹ of the present complex. It is possibly even shorter than the Cu-N(7) distance for the nonhydrogen bonded, neutral theophylline ligand in the complex [nitratobis(aquo)bis(theophylline)copper(II)]⁺ (Table IV). The shortness of the Cu-N(7) bond is probably a result of the chelation of the theophylline monoanion.

The remaining bond lengths in the primary coordination sphere closely resemble those we have found in the complex [(*N*-salicylidene-*N'*-methylethylenediamine)(cytosine)copper(II)]⁺, where the cytosine is chelated through N(3) and O(2).³⁵ The Cu-N(20) distance is slightly longer here, 2.068

Table V. Nonhydrogen Atom Interatomic Distances and Angles

(a) Primary Coordination Sphere about the Copper Atom			
Bond Lengths, Å			
Cu-N(7)	1.956 (3)	Cu-N(20)	2.068 (3)
Cu-N(17)	1.939 (3)	Cu-O(10)	1.930 (2)
		Cu-O(6)	2.919 (3)
Bond Angles, deg			
N(7)-Cu-N(7)	176.3 (1)	N(17)-Cu-N(20)	84.8 (1)
N(7)-Cu-N(20)	93.4 (1)	N(17)-Cu-O(10)	90.2 (1)
N(7)-Cu-O(10)	91.6 (1)	N(20)-Cu-O(10)	175.0 (1)
N(7)-Cu-O(6)	73.2 (1)	N(20)-Cu-O(6)	94.7 (1)
N(17)-Cu-O(6)	110.1 (1)	O(10)-Cu-O(6)	87.5 (1)
(b) The <i>N</i> -3,4-Benzosalicylidene- <i>N,N'</i> -dimethylethylenediamine			
Chelate Ligand Bond Lengths, Å			
O(10)-C(10)	1.318 (4)	C(15)-C(16)	1.435 (4)
C(10)-C(11)	1.416 (5)	C(16)-N(17)	1.288 (4)
C(11)-C(12)	1.363 (5)	N(17)-C(18)	1.475 (5)
C(12)-C(13)	1.438 (5)	C(18)-C(19)	1.503 (5)
C(13)-C(14)	1.400 (4)	C(19)-N(20)	1.479 (5)
C(13)-C(21)	1.427 (5)	N(20)-C(20)	1.495 (5)
C(14)-C(24)	1.413 (5)	N(20)-C(26)	1.477 (5)
C(14)-C(15)	1.469 (4)	C(21)-C(22)	1.357 (6)
C(15)-C(10)	1.408 (4)	C(22)-C(23)	1.403 (6)
		C(23)-C(24)	1.382 (6)
Bond Angles, deg			
Cu-O(10)-C(10)	127.6 (2)	C(16)-N(17)-C(18)	119.0 (3)
O(10)-C(10)-C(11)	116.6 (3)	Cu-N(17)-C(16)	127.9 (2)
O(10)-C(10)-C(15)	124.1 (3)	Cu-N(17)-C(18)	113.0 (2)
C(11)-C(10)-C(15)	119.3 (3)	N(17)-C(18)-C(19)	106.9 (3)
C(10)-C(11)-C(12)	121.7 (3)	C(18)-C(19)-N(20)	110.2 (3)
C(11)-C(12)-C(13)	120.8 (3)	Cu-N(20)-C(19)	105.1 (2)
C(12)-C(13)-C(14)	119.4 (3)	Cu-N(20)-C(20)	114.9 (2)
C(12)-C(13)-C(21)	119.7 (3)	Cu-N(20)-C(26)	108.3 (2)
C(14)-C(13)-C(21)	120.9 (3)	C(19)-N(20)-C(20)	108.2 (3)
C(13)-C(14)-C(15)	119.1 (3)	C(19)-N(20)-C(26)	111.8 (3)
C(13)-C(14)-C(24)	117.5 (3)	C(20)-N(20)-C(26)	108.5 (3)
C(15)-C(14)-C(24)	123.4 (3)	C(13)-C(21)-C(22)	119.8 (4)
C(10)-C(15)-C(14)	119.5 (3)	C(21)-C(22)-C(23)	120.3 (4)
C(10)-C(15)-C(16)	121.2 (3)	C(22)-C(23)-C(24)	120.2 (4)
C(14)-C(15)-C(16)	119.2 (3)	C(14)-C(24)-C(23)	121.2 (3)
C(15)-C(16)-N(17)	125.8 (3)		
(c) The Theophylline Anion			
Bond Lengths, Å			
N(1)-C(1)	1.465 (6)	N(7)-C(5)	1.371 (4)
N(1)-C(2)	1.393 (5)	N(7)-C(8)	1.338 (5)
N(1)-C(6)	1.404 (5)	N(9)-C(4)	1.336 (4)
N(3)-C(2)	1.373 (5)	N(9)-C(8)	1.343 (5)
N(3)-C(3)	1.448 (5)	C(2)-O(2)	1.235 (5)
N(3)-C(4)	1.391 (4)	C(4)-C(5)	1.369 (4)
C(5)-C(6)	1.426 (4)	C(6)-O(6)	1.225 (4)
Bond Angles, deg			
C(1)-N(1)-C(2)	116.6 (3)	N(3)-C(2)-O(2)	121.3 (3)
C(1)-N(1)-C(6)	116.6 (3)	N(1)-C(2)-N(3)	117.8 (3)
C(2)-N(1)-C(6)	126.8 (3)	N(3)-C(4)-N(9)	127.3 (3)
C(2)-N(3)-C(3)	119.9 (3)	N(3)-C(4)-C(5)	121.3 (3)
C(2)-N(3)-C(4)	119.1 (3)	N(9)-C(4)-C(5)	111.4 (3)
C(3)-N(3)-C(4)	121.0 (3)	N(7)-C(5)-C(4)	107.6 (3)
Cu-N(7)-C(5)	117.8 (2)	N(7)-C(5)-C(6)	129.0 (3)
Cu-N(7)-C(8)	138.9 (2)	C(4)-C(5)-C(6)	123.3 (3)
C(5)-N(7)-C(8)	102.9 (3)	N(1)-C(6)-O(6)	122.6 (3)
C(4)-N(9)-C(8)	102.2 (3)	N(1)-C(6)-C(5)	111.6 (3)
N(1)-C(2)-O(2)	120.9 (3)	C(5)-C(6)-O(6)	125.8 (3)
		N(7)-C(8)-N(9)	115.9 (3)

(3) Å, than is found in the cytosine complex, 2.048 (1) Å, but this increase can be directly attributed to the addition of the second methyl substituent to the *N*-methylethylenediamine terminus. For example, the observed length is very similar to that found in the binuclear complex [di- μ -hydroxo-bis[2-(2-dimethylaminoethyl)pyridine]]dicopper(II)]²⁺,³⁷ 2.056 (2)

Å. The N(20)-Cu-O(10) and N(7)-Cu-N(17) bond angles of 175.0 (1) and 174.6 (1)° are in excellent agreement with those in the cytosine complex, 175.5 (1) and 174.6 (1)°, and is a result of the fact that in each of the complexes the equatorial planes are reasonably planar (Table VI). The Cu-O(6) bond is considerably more on axis than the Cu-O(2) bond in

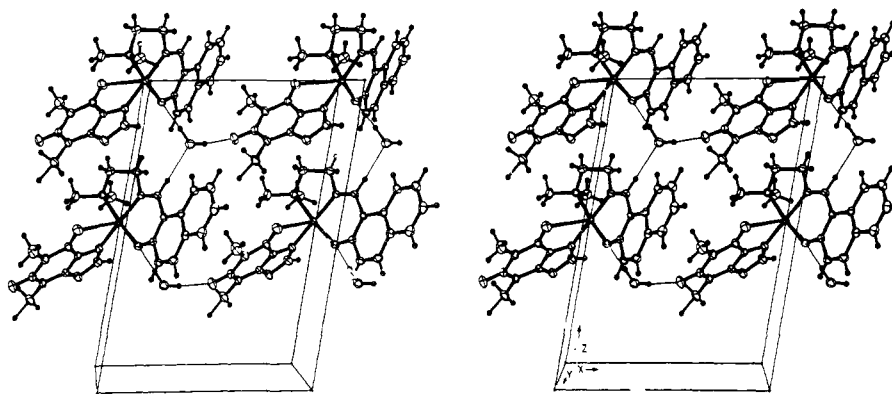


Figure 3. A stereoview of the crystal packing. Intra- and intermolecular hydrogen bonds are indicated by narrow lines, including one CH...O contact, see text.

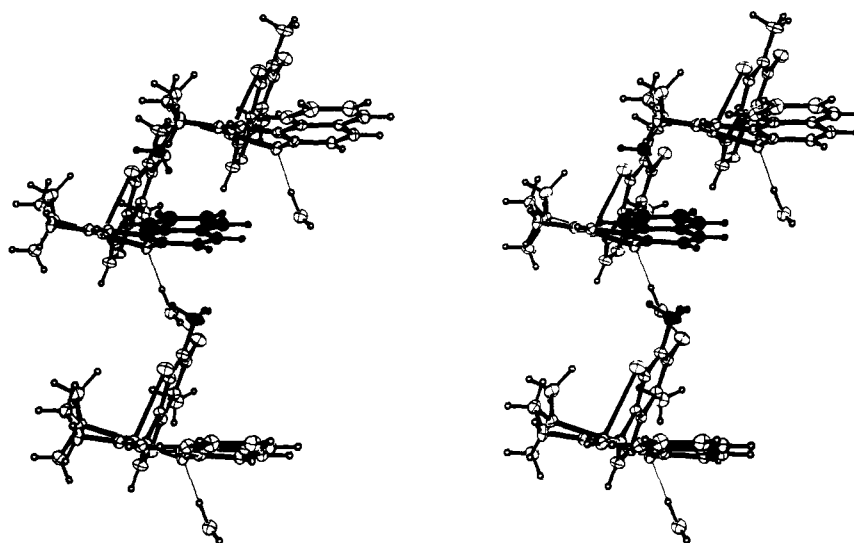


Figure 4. A stereoview of the "pinning" of the naphthylidene ring.

the cytosine complex.³⁵ The largest observed deviations from 90° are in the N(17)–Cu–O(6), 20.1°, and N(7)–Cu–O(6), –16.8°, angles (Table V).

The parameters in the theophylline monoanion are in good agreement with other determinations^{20,21,27} for Cu(II) complexes, except for a slight decrease of about 0.02 Å in the N(7)–C(5) bond and some adjustment in the bond angles at C(5) and C(6) of up to 3°. The decrease in the N(7)–C(5) bond may be correlated with the strength of the Cu–N(7) interaction, while the angular adjustments at C(5) and C(6) are probably a consequence of the chelation of O(6), as O(6) is 0.102 Å out of the mean plane of the theophylline anion (Table VI) toward the Cu. The out-of-plane deviation of O(6) is substantially larger than in other systems,^{20,21,27} where Cu and O(6) are normally on the opposite sides of the mean plane.

The coordinated theophylline monoanion is nearly planar (Table VI), with the fold about the C(4)–C(5) bond of only 0.5 (3)°. The degree of planarity is considerably greater here than in other determinations, where the fold about C(4)–C(5) ranges from 2.0 (3)²⁰ to 3.3 (2)°.²⁷

The *N*-3,4-benzosalicylidene-*N',N'*-dimethylethylenediamine ligand parameters are in good agreement with other results,³⁸ and in substantial agreement with its monomethyl analogue.²¹ There are some minor adjustments in the salicylidene ring relative to the monomethyl complex: O(10)–C(10) has increased from 1.298 (4), monomethyl, to 1.318 (4) Å, dimethyl, with a similar increase in the C(12)–C(13) bond length and a decrease on the same order in the C(13)–C(14)

bond length. There are also angular adjustments in the salicylidene ring of up to 2° as a result of the bond length perturbations. The naphthylidene ring is quite planar (Table VI), with a fold about the fusion bond C(13)–C(14) of 2.7 (3)°, which is slightly larger than that observed in the monomethyl analogue,²¹ 2.0 (3)°, and may account for the minor changes in bond lengths and angles mentioned above.

Crystal Packing. The crystal packing is illustrated in the stereoview of Figure 3. One of the principal features is the coupling of translationally-related complexes via hydrogen bonds from the water crystallization to O(2) of the theophylline ring and O(10) of the salicylidene ring (O(31)–H(31) = 0.87 Å, O(31)...O(2)[1 + x, y, z] = 2.832 (4) Å, H(31)...O(2) = 1.98 Å, O(31)–H(31)...O(2) angle = 170°; O(31)–H(32) = 1.01 Å, O(31)...O(10)[x, y, z] = 2.835 (4) Å, O(31)–H(32)...O(10) angle = 177°, see Figure 3). The water of crystallization is also involved in a moderately strong C–H...O interaction with the methine hydrogen of the salicylidene ring (C(16)–H(16) = 0.95, C(16)...O(31)[x, –y, –½ + z] = 3.247 (4), H(16)...O(31) = 2.33 Å, C(16)–H(16)...O(31) angle = 162°, Figure 3). These three interactions provide roughly a trigonal planar environment about the water molecule and the set is extended to trigonal bipyramidal via interactions involving the naphthylidene ring (Figure 3). The composite of interactions about the lattice water leads to a rather strong binding of the water and to low thermal motion (Table II).

The second principal packing interaction involves the

Table VI. Least-Squares Planes and the Deviations (Å) of Individual Atoms from These Planes^a

(a) Primary Coordination Plane Including the Copper Atom ($-0.6539X - 0.7241Y - 0.2193Z = -0.4936 \text{ \AA}$)			
Cu	0.026	N(17)	-0.030
O(10)	0.016	N(20)	0.015
N(7)	-0.028	O(6)	2.791*
(b) The 3,4-Benzosalicylidene Ring ($-0.8164X - 0.4705Y - 0.3348Z = -0.9366 \text{ \AA}$)			
C(10)	0.010	C(15)	0.042
C(11)	-0.048	C(21)	0.035
C(12)	-0.015	C(22)	0.008
C(13)	0.021	C(23)	-0.034
C(14)	0.009	C(24)	-0.028
(c) Nine-Atom Framework of the Coordinated Theophylline ($-0.4784X + 0.5402Y - 0.6923Z = 0.2132 \text{ \AA}$)			
N(1)	0.003	C(5)	-0.012
C(2)	-0.024	C(6)	0.022
N(3)	0.016	N(7)	-0.012
C(4)	0.000	C(8)	0.001
O(2)	-0.070*	N(9)	0.007
O(6)	0.102*	C(1)	-0.007*
Cu	0.135*	C(3)	0.053*
(d) Pyrimidine Ring of the Coordinated Theophylline Monoanion ($-0.4815X + 0.5406Y - 0.6899Z = 0.2300 \text{ \AA}$)			
N(1)	0.002	C(4)	0.000
C(2)	-0.020	C(5)	-0.018
N(3)	0.020	C(6)	0.016
(e) Imidazole Ring of the Coordinated Theophylline Monoanion ($-0.4765X + 0.5339Y - 0.6985Z = 0.1822 \text{ \AA}$)			
N(7)	0.000	C(4)	0.001
C(8)	0.001	C(5)	0.000
N(9)	-0.001		

^a In each of the equations of the planes, X , Y , and Z are coordinates (Å) referred to the orthogonal axes a , b , and c^* . Atoms designated by an asterisk were given zero weight in calculating the plane; other atoms were weighted equally.

"pinning" of the naphthylidene ring by the methyl groups C(26)H₃ of the benzosalicylidene chelate and C(3)H₃ of the theophylline monoanion ring (Figures 3 and 4).

Acknowledgment. This investigation was supported by the National Institutes of Health, Public Health Service Grant No. GM 20544.

Supplementary Material Available: A listing of observed and cal-

culated structure factor amplitudes (17 pages). Ordering information is given on any current masthead page.

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