# *X*-Ray Structure of a Ternary Complex, Copper(II)–Inosine 5′-Monophosphate–Benzimidazole. The First Example for the Absence of Direct Metal–Nucleotide Interaction†

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The unprecedented absence of direct metal–nucleotide interaction has been observed in the *X*-ray structure of the ternary metal nucleotide system $[Cu(bzim)(H_2O)_5]^{2+}[IMP]^{2-}\cdot 3H_2O$ [IMP = inosine 5′-monophosphate(2−), bzim = benzimidazole). The complex crystallizes in the space group $P2_1$ with $a$ = 7.013(2), $b$ = 13.179(9), $c$ = 14.565(9) Å, β = 94.82(4)°, and $Z$ = 2. The structure was solved by the heavy-atom method and refined by full-matrix least squares on the basis of 1 761 observed ($I \geqslant 3\sigma_I$) reflections to final $R$ and $R'$ values of 0.034 and 0.036 respectively. The $Cu^{II}$ has a distorted octahedral co-ordination with a nitrogen of the bzim ligand [Cu–N 1.947(5) Å] and three oxygens of water molecules in the basal plane [mean Cu–O 2.017(3) Å] and two more water oxygens at axial positions [Cu–O 2.194(6) and 2.732(5) Å]. The nucleotide base stacks with the bzim ligand at an average distance of 3.5 Å and an angle of 22°. In the lattice, N(7) of the base is linked to a lattice water through a hydrogen bond, while all the phosphate oxygens are involved in hydrogen bonds with co-ordinated as well as lattice water molecules. The co-ordination behaviour of IMP to $Cu^{II}$ is compared in structures containing different π-aromatic amines in order to assess the influence of the ternary ligand in complex formation. The present results indicate that, apart from the commonly observed phosphate binding, other modes of co-ordination are possible, these being influenced mainly by the π-accepting properties of the ternary ligand.

There has been a burgeoning interest in the study of metal-ion interactions with nucleic acid constituents in recent years. This has been mainly due to (*i*) the involvement of metal ions in several nucleic acid processes,[1] (*ii*) the use of certain platinum complexes such as *cis*-platin as antitumour agents[2] that are believed to act by inhibiting DNA synthesis, (*iii*) the use of the unique properties of metals as probes in nucleic acid chemistry for electron microscopic investigations, or for isolation of nucleic acid samples that contain specific bases.[3–6]

It has been shown that the co-ordination behaviour of a nucleotide changes in going from a binary to a ternary complex,[7] in which one additional ligand is introduced. Ternary metal ion–nucleotide complexes containing aromatic heterocyclic amines are of particular interest due to the fact that they can be regarded as simple models for the naturally occurring substrate–metal ion–aromatic amino acid centres found in proteins.[7a] In recent years, considerable attention has been focused on copper(II) complexes containing the imidazole (im) group as a ligand, since this group is one of the important and versatile binding sites for $Cu^{II}$ in many biological systems.[8–11] The im ring as a histidine moiety and the benzimidazole (bzim) ring as its 5,6-dimethyl derivative function as ligands towards transition-metal ions in a variety of biologically important molecules, including haem systems, vitamin $B_{12}$ and its derivatives, and several metalloproteins.[8]

Results from solution studies[7,12–15] reveal the binding of the nucleotide through the phosphate group in preference to the nucleobase in a ternary complex containing π-aromatic amines such as bipy, dpa, and phen.‡ This has largely been confirmed from the results of solid-state studies.[16–21] Solution studies have suggested similar discriminating properties for the im group.[9,10,12] However, the structure of $[Cu(IMP)_2(im)_{0.8}\text{-}H_2O)_{3.2}]$[22] reveals metal binding to N(7) of the base rather than to the phosphate. This unexpected result prompted us to examine the solid-state structures of $Cu^{II}$–5′-IMP complexes with substituted imidazoles. The present paper reports the first structural study of a metal complex involving bzim, wherein the nucleotide remains unco-ordinated to the metal. A preliminary communication on this novel type of interaction has been published.[23]

## Experimental

The complex was prepared by vapour diffusion of an aqueous solution of $Cu(NO_3)_2$, $Na_2(IMP)$, and bzim, each $5 \times 10^{-3}$ mol dm$^{-3}$, against t-butyl alcohol. The solution was adjusted to pH 6.0 using dilute $HNO_3$ (0.01 mol dm$^{-3}$). Light blue plate-like crystals were formed after about 1 week (Found: C, 30.6; H, 3.9; N, 12.5. Calc. for $C_{17}H_{33}CuN_6O_{16}P$: C, 30.4; H, 4.9; N, 12.5%).

*Physical Measurements.*—The i.r. spectra were recorded with a Perkin-Elmer 599 spectrometer on KBr pellets in the range 4 000—200 cm$^{-1}$. The e.s.r. spectrum was recorded on a Varian E 109 spectrometer at *X*-band. The magnetic field was centred around 3 200 G with a scan range of 2 KG. The microwave frequency used in the experiment was $9.05 \times 10^9$ s$^{-1}$.

*Crystallography.*—Details regarding the data collection and processing are presented in Table 1. The data were corrected for

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† *Supplementary data available:* see Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1989, Issue 1, pp. xvii—xx.

Abbreviations used as in accord with the recommendations of the I.U.P.A.C.—I.U.B. Commission on Biochemical Nomenclature, *Eur. J. Biochem.*, 1970, **15**, 203.

*Non-S.I. unit employed:* G = $10^{-4}$ T.

‡ bipy = 2,2′-bipyridyl, dpa = bis(2-pyridyl)amine, phen = 1,10-phenanthroline, dien = diethylenetriamine, en = ethylenediamine, terpy = 2,2′:6′,2″-terpyridine, AMP, IMP, UMP, and CMP = the 5′- monophosphates(2−) of adenosine, inosine, uridine, and cytidine, 3′-GMP = guanosine 3′-monophosphate(2−), ATP = adenosine 5′- triphosphate(2−), $IMPH_{-1}$ = inosine 5′-monophosphate(3−), IMPH = inosine 5′-monophosphate(1−), dCpG = deoxycytidylyl(3′,5′)deoxyguanosinate(1−), theo = theophylline(1,3-dimethyl-2,6-dioxopurine).

**Table 1.** Cryatal data for $[Cu(bzim)(H_2O)_5]^{2+}[IMP]^{2-}\cdot 3H_2O$

| | |
|---|---|
| Formula | $C_{17}H_{33}CuN_6O_{16}P$ |
| $M$ | 671.62 |
| Crystal system | Monoclinic |
| Space group | $P2_1$ |
| $a$/Å | 7.013(2) |
| $b$/Å | 13.179(9) |
| $c$/Å | 14.565(9) |
| β/° | 94.82(4) |
| $U$/Å$^3$ | 1 341(1) |
| $Z$ | 2 |
| $D_m$/g cm$^{-3}$ | 1.64 |
| $D_c$/g cm$^{-3}$ | 1.65 |
| $F$(000) | 694 |
| μ/cm$^{-1}$ | 9.55 |
| λ/Å | 0.7107 |
| Crystal dimensions/mm | 0.55 × 0.55 × 0.10 |
| 2θ Range/° | 4.5—45 |
| Scan mode | θ—2θ |
| Scan speed/° min$^{-1}$ | 2.5—12.5 |
| Scan width (Δθ) | 0.75 + 0.45 tanθ |
| Reflections | |
| measured | 2 010 |
| used ($I \geqslant 3\sigma_I$) | 1 761 |
| $R = \Sigma\|\|F_o\| - \|F_c\|\|/\Sigma F_o$ | 0.034 |
| $R' = [\Sigma w(\|F_o\| - \|F_c\|)^2/\Sigma wF_o^2]^{\frac{1}{2}}$ | 0.036 |

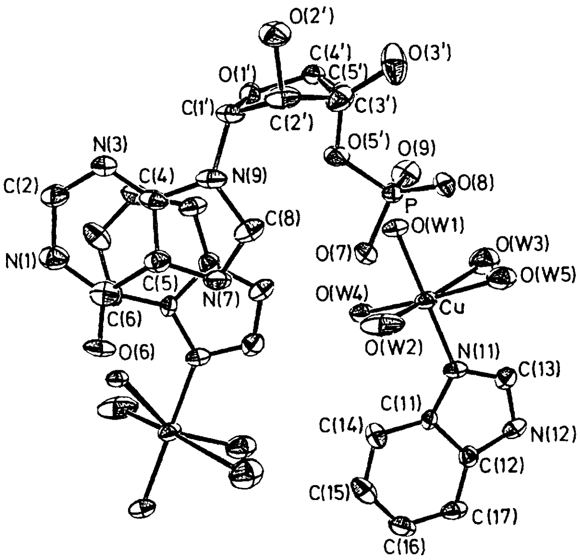

**Figure 1.** ORTEP drawing of $Cu(IMP)(bzim)(H_2O)_5$ showing the atom numbering and thermal motion ellipsoids (50% probability level) for non-hydrogen atoms. The screw-related $[Cu(bzim)(H_2O)_5]^{2+}$ cation is also included to display the purine base and bzim ring stacking (view down the $a$ axis)

Lorentz and polarization effects. An absorption correction was applied using φ-scan data.[24]

*Solution and refinement of the structure.* The structure was solved by conventional Patterson and Fourier techniques and refined by a full-matrix least-squares procedure. The non-hydrogen atoms were refined anisotropically. All the hydrogen atoms, including those belonging to eight water molecules, were located from difference electron-density maps. These were included in subsequent calculations with their thermal parameters set equal to 0.019 + $U_{iso}$ of the heavy atom to which they were bonded. The shifts in parameters in the last cycle were less than 0.1σ. The weighting scheme employed was of the form $w = [\sigma^2(F_o) + 0.0001(F_o)^2]^{-1}$. Final $R$ and $R'$ values were 0.034 and 0.036. The final difference electron-density map revealed no peak higher than 0.2 e Å$^{-3}$.

**Table 2.** Fractional atomic co-ordinates (× $10^4$) for non-hydrogen atoms of $[Cu(bzim)(H_2O)_5][IMP]\cdot 3H_2O$ with estimated standard deviations (e.s.d.s) in parentheses

| Atom | $x$ | $y$ | $z$ |
|---|---|---|---|
| Cu | 3 393(1) | 5 000(0) | 918(1) |
| P | 8 928(2) | 4 096(1) | 2 819(1) |
| O(7) | 8 809(7) | 3 645(4) | 1 857(3) |
| O(8) | 463(6) | 4 900(4) | 2 942(3) |
| O(9) | 7 042(7) | 4 452(4) | 3 109(4) |
| N(1) | 1 775(9) | −1 781(5) | 2 163(4) |
| C(2) | 2 053(10) | −1 699(6) | 3 105(5) |
| N(3) | 2 463(9) | −857(5) | 3 539(4) |
| C(4) | 2 589(9) | −50(7) | 2 982(4) |
| C(5) | 2 355(9) | −54(7) | 2 037(4) |
| C(6) | 1 887(9) | −967(6) | 1 565(5) |
| O(6) | 1 637(7) | −1 114(4) | 724(3) |
| N(7) | 2 556(9) | 914(5) | 1 700(4) |
| C(8) | 2 900(11) | 1 498(6) | 2 431(5) |
| N(9) | 2 990(8) | 918(5) | 3 249(4) |
| C(1′) | 3 321(10) | 1 272(6) | 4 206(4) |
| C(2′) | 4 808(9) | 2 105(6) | 4 371(5) |
| C(3′) | 3 571(11) | 3 055(6) | 4 317(5) |
| C(4′) | 1 823(9) | 2 721(5) | 4 741(4) |
| C(5′) | 1(10) | 3 263(6) | 4 423(5) |
| O(1′) | 1 596(6) | 1 659(4) | 4 502(3) |
| O(2′) | 5 658(7) | 2 019(4) | 5 287(3) |
| O(3′) | 4 407(8) | 3 923(4) | 4 754(5) |
| O(5′) | 9 612(6) | 3 137(4) | 3 441(3) |
| N(11) | 2 931(7) | 5 570(4) | −314(3) |
| C(11) | 2 799(8) | 5 094(5) | −1 194(4) |
| C(12) | 2 323(9) | 5 848(5) | −1 854(4) |
| N(12) | 2 135(7) | 6 747(4) | −1 381(4) |
| C(13) | 2 499(10) | 6 537(5) | −488(5) |
| C(14) | 3 126(10) | 4 116(5) | −1 446(5) |
| C(15) | 2 942(10) | 3 898(6) | −2 382(5) |
| C(16) | 2 398(11) | 4 632(6) | −3 049(5) |
| C(17) | 2 061(9) | 5 622(6) | −2 796(4) |
| O(W1) | 3 644(6) | 4 431(4) | 2 162(3) |
| O(W2) | 1 349(6) | 3 921(4) | 632(3) |
| O(W3) | 4 978(7) | 6 262(4) | 1 324(3) |
| O(W4) | 5 831(7) | 4 060(5) | 595(3) |
| O(W5) | 667(7) | 6 274(4) | 1 500(4) |
| O(W6) | 7 686(8) | 6 784(4) | 98(3) |
| O(W7) | 8 747(8) | 961(5) | 5 504(4) |
| O(W8) | 3 754(8) | 1 464(4) | 6 879(3) |

The neutral scattering factors for Cu were taken from ref. 25; the scattering factors for H, C, N, O, and P were as available from the SHELX 76 program.[26] Anomalous dispersion corrections were applied to the scattering factors of all the non-hydrogen atoms.[27] The correct optical form of the nucleotide was identified from the known absolute configuration of D-ribose. Calculations were performed on a DEC 1090 computer using the SHELX 76 system of programs for Fourier and least-squares calculations and ORTEP II[28] and PLUTO 78[29] for diagrams. Final atomic co-ordinates for the non-hydrogen atoms are given in Table 2.

Additional material available from the Cambridge Crystallographic Data Centre comprises H-atom co-ordinates, thermal parameters, and remaining distances and angles.

## Results

The molecular structure and atom-labelling scheme are shown in Figure 1, selected bond distances and angles in Table 3.

*Metal co-ordination.* The $Cu^{II}$ has a distorted octahedral (4 + 1 + 1) geometry.[30] The bzim ligand co-ordinates through the

**Table 3.** Bond distances involving non-hydrogen atoms (Å) with their e.s.d.s in parentheses

| | | | |
|---|---|---|---|
| Cu–N(11) | 1.947(5) | N(9)–C(1′) | 1.470(8) |
| Cu–O(W1) | 1.955(5) | C(1′)–C(2′) | 1.519(10) |
| Cu–O(W2) | 2.037(5) | C(1′)–O(1′) | 1.413(8) |
| Cu–O(W3) | 2.059(5) | C(2′)–C(3′) | 1.522(11) |
| Cu–O(W4) | 2.194(6) | C(2′)–O(2′) | 1.419(8) |
| Cu–O(W5) | 2.732(5) | C(3′)–C(4′) | 1.485(10) |
| P–O(7) | 1.518(5) | C(3′)–O(3′) | 1.412(10) |
| P–O(8) | 1.510(5) | C(4′)–C(5′) | 1.503(10) |
| P–O(9) | 1.497(5) | C(4′)–O(1′) | 1.448(8) |
| P–O(5′) | 1.605(5) | C(5′)–O(5′) | 1.443(8) |
| N(1)–C(2) | 1.374(9) | N(11)–C(11) | 1.423(8) |
| N(1)–C(6) | 1.388(10) | N(11)–C(13) | 1.329(8) |
| C(2)–N(3) | 1.297(10) | C(11)–C(12) | 1.403(9) |
| N(3)–C(4) | 1.345(10) | C(11)–C(14) | 1.365(9) |
| C(4)–C(5) | 1.372(8) | C(12)–N(12) | 1.382(8) |
| C(4)–N(9) | 1.356(11) | C(12)–C(17) | 1.401(8) |
| C(5)–C(6) | 1.411(11) | N(12)–C(13) | 1.333(9) |
| C(5)–N(7) | 1.378(11) | C(14)–C(15) | 1.389(10) |
| C(6)–O(6) | 1.238(8) | C(15)–C(16) | 1.401(11) |
| N(7)–C(8) | 1.320(10) | C(16)–C(17) | 1.382(11) |
| C(8)–N(9) | 1.413(10) | | |

**Table 4.** Bond angles (°) involving non-hydrogen atoms with e.s.d.s in parentheses

| | | | |
|---|---|---|---|
| N(11)–Cu–O(W1) | 175.6(2) | C(5)–N(7)–C(8) | 105.7(6) |
| N(11)–Cu–O(W2) | 91.2(2) | N(7)–C(8)–N(9) | 110.9(6) |
| N(11)–Cu–O(W3) | 89.8(2) | C(4)–N(9)–C(8) | 105.9(6) |
| N(11)–Cu–O(W4) | 95.3(2) | C(4)–N(9)–C(1′) | 125.7(6) |
| N(11)–Cu–O(W5) | 89.0(2) | C(8)–N(9)–C(1′) | 128.4(6) |
| O(W1)–Cu–O(W2) | 85.9(2) | N(9)–C(1′)–C(2′) | 115.5(6) |
| O(W1)–Cu–O(W3) | 92.3(2) | N(9)–C(1′)–O(1′) | 109.4(5) |
| O(W1)–Cu–O(W4) | 88.3(2) | C(2′)–C(1′)–O(1′) | 106.5(5) |
| O(W1)–Cu–O(W5) | 87.7(2) | C(1′)–C(2′)–C(3′) | 101.9(6) |
| O(W2)–Cu–O(W3) | 167.4(2) | C(1′)–C(2′)–O(2′) | 108.6(6) |
| O(W2)–Cu–O(W4) | 96.3(2) | C(3′)–C(2′)–O(2′) | 107.9(6) |
| O(W2)–Cu–O(W5) | 89.6(2) | C(2′)–C(3′)–C(4′) | 102.8(6) |
| O(W3)–Cu–O(W4) | 96.1(2) | C(2′)–C(3′)–O(3′) | 115.5(6) |
| O(W3)–Cu–O(W5) | 77.8(2) | C(4′)–C(3′)–O(3′) | 112.2(6) |
| O(W4)–Cu–O(W5) | 172.6(2) | C(3′)–C(4′)–C(5′) | 116.2(6) |
| O(7)–P–O(8) | 111.6(3) | C(3′)–C(4′)–O(1′) | 105.3(5) |
| O(7)–P–O(9) | 113.7(3) | C(5′)–C(4′)–O(1′) | 108.2(5) |
| O(7)–P–O(5′) | 101.7(3) | C(1′)–O(1′)–C(4′) | 110.0(5) |
| O(8)–P–O(9) | 112.6(3) | Cu–N(11)–C(11) | 130.8(4) |
| O(8)–P–O(5′) | 108.0(3) | Cu–N(11)–C(13) | 124.3(4) |
| O(9)–P–O(5′) | 108.5(3) | C(11)–N(11)–C(13) | 104.7(5) |
| C(2)–N(1)–C(6) | 123.7(6) | N(11)–C(11)–C(12) | 107.4(5) |
| N(1)–C(2)–N(3) | 124.1(7) | N(11)–C(11)–C(14) | 131.2(6) |
| C(2)–N(3)–C(4) | 113.9(6) | C(12)–C(11)–C(14) | 121.3(6) |
| N(3)–C(4)–C(5) | 126.4(7) | C(11)–C(12)–N(12) | 107.0(5) |
| N(3)–C(4)–N(9) | 126.4(7) | C(11)–C(12)–C(17) | 121.6(6) |
| C(5)–C(4)–N(9) | 107.2(6) | N(12)–C(12)–C(17) | 131.3(6) |
| C(4)–C(5)–C(6) | 119.7(7) | C(12)–N(12)–C(13) | 106.8(5) |
| C(4)–C(5)–N(7) | 110.3(6) | N(11)–C(13)–N(12) | 114.0(6) |
| C(6)–C(5)–N(7) | 130.0(7) | C(11)–C(14)–C(15) | 117.1(6) |
| N(1)–C(6)–C(5) | 112.1(6) | C(14)–C(15)–C(16) | 122.4(7) |
| N(1)–C(6)–O(6) | 119.3(6) | C(15)–C(16)–C(17) | 120.7(7) |
| C(5)–C(6)–O(6) | 128.6(7) | C(12)–C(17)–C(16) | 116.8(6) |

nitrogen atom, N(11), at the equatorial position [Cu–N(bzim) = 1.947(5) Å], while the remaining sites in the basal plane are occupied by water oxygen atoms, O(W1), O(W2), and O(W3) [mean Cu–O 2.017(3) Å]. The axial positions are occupied by water oxygens, O(W4) and O(W5) [Cu–O(W4) 2.194(6) and Cu–O(W5) 2.732(5) Å]. Note that the equatorial bond distance Cu–O(W1) [1.955(5) Å], where O(W1) is *trans* to the bzim N, is significantly shorter than the other two equatorial bonds, while the axial bond distance involving O(W5) and the metal ion is significantly longer than the other. The bzim ligand is inclined to the equatorial plane containing N(11), O(W1), O(W2), and O(W3) by 46.5°. Possibly the axial ligand O(W5) is pushed away from the Cu in order to overcome the unfavourable steric interactions with the bzim group. Notwithstanding this long Cu–O(W5) distance, O(W5) makes a very short contact of 3.28 Å with C(13) of bzim. The co-ordination geometry in the present structure is similar to that observed in [Cu(IMP)$_2$(dien)][31] and [Cd(UMP)(dpa)(H$_2$O)$_2$].[19] The Cu ion deviates slightly [0.154(1) Å] from the equatorial plane towards the axial ligand, O(W4). Among the three equatorial planes of the octahedron, that involving N(11), O(W1), and the axial ligands shows a slight tetrahedral distortion (maximum and minimum deviations 0.12 and 0.05 Å respectively), whereas the other two are virtually planar. The *cis* bond angles around the metal range between 77.8 and 96.3°. The *trans* bond angles are 167.4, 172.6, and 175.6°.

*Molecular Structure.*—The bond parameters in the nucleotide (Table 3) are in good agreement with values reported for other complexes[32] containing IMP. The ribose moiety displays the usual C(3′) *endo*[33] puckering mode. The orientation of the sugar with respect to the purine framework is *anti*, $\chi_{CN} = -96.9(7)°$. The conformation about the C(4′)–C(5′) bond is *gauche–gauche*, the angles $\psi_{OO}$ and $\psi_{OC}$ being $-58.9(6)$ and 59.2(7)° respectively. This conformation is very common in complexes of the type M(nucleotide)(H$_2$O)$_5$ and in other ternary metal–nucleotide complexes.[19] The torsion $\varphi$ is $-135.9(5)°$. The dihedral angle between the plane of the purine base and the sugar is 82.1°. The purine plane is approximately planar, with the imidazole and pyrimidine rings inclined to each other by an angle of 1.7° about the C(4)–C(5) bond. The deviation of (C3′) from the best plane through the four atoms of the furanose ring is 0.531(7) Å. The atoms C(5) and C(8) show slight deviations of 0.022(7) and 0.033(5) Å from the plane of the purine ring, while the exocyclic atoms O(6) and C(1′) deviate by 0.016(5) and 0.024(7) Å respectively. The bzim ring is virtually planar, the dihedral angle between the imidazole and the phenyl ring planes being 1.0°. The bond parameters of the bzim group agree well with those reported earlier.[34]

*Stacking and Hydrogen-bonding Interactions.*—In the case of molecules containing planar π-aromatic rings there is a general tendency for parallel stacking between the planar groups with a separation of *ca.* 3.5 Å. The only stacking interaction in the present crystal structure is the inter-complex base–bzim stacking (Figures 2 and 3). The screw-related bzim ring overlaps with the purine base at an average distance of 3.5 Å, the dihedral angle between the two groups being 22°. Unit-cell translation along *a* results in a stacking pattern of the type -ABABA- (A = nucleotide base; B = π-aromatic amine). No A–A, B–B type of self-stacking is observed as in the case of [{Cu(UMP)(dpa)(H$_2$O)}$_2$],[17] [{Cu(IMP)(dpa)(H$_2$O)}$_2$],[20,21] and [{Cu(CMP)(dpa)(H$_2$O)}$_2$].[19] The imidazole moiety of the purine base stacks with the imidazole part of the bzim ring (Figure 1), the closest interaction being N(7) ··· C(12) 3.47 and N(7) ··· N(12) 3.48 Å. The pyrimidine ring of the purine base overlaps partly with the phenyl ring of the bzim ligands, with short contacts being C(4) ··· C(16) 3.50 and C(6) ··· C(14) 3.49 Å. A similar AB type of stacking is also observed in [{Cu(3′-GMP)(phen)(H$_2$O)}$_2$][18] and [{Cu(AMPH)(bipy)(H$_2$O)}$_2$][16] where the purine base and the π-aromatic amine are disposed parallel to each other in the complex. The other significant intercomplex base–sugar interactions involving the ribose hydroxyls are O(2′) ··· N(3) 3.48, O(2′) ··· C(2) 3.18, and O(3′) ··· N(3) 3.18 Å.

Apart from base stacking, the crystal structure (Figure 3) is stabilized by hydrogen bonding. The possible hydrogen bonds are listed in Table 5 and shown in Figure 2. Water molecules are involved in all the hydrogen bonds, the only exception being that between phosphate oxygen O(7) and the bzim nitrogen N(12). This bond is of interest, since it represents a phosphate–bzim interaction. The phosphate group is rigidly held in the lattice through an extensive network of hydrogen bonds. The O(7) of phosphate accepts two protons from co-ordinated waters, O(W2) and O(W4); O(8) forms three hydrogen bonds, two with co-ordinated waters, O(W1) and O(W5), and the third with a lattice water, O(W7). Further, O(9) acts as a proton acceptor from O(W1) and O(W8). In the purine base, atoms O(6) and N(7) are proton acceptors, while N(1) acts as a donor. The atoms of the ribose group, O(1′) and O(2′), are also involved in hydrogen bonding with O(W7) and O(W8) respectively. There is also an intricate system of hydrogen bonds involving the water molecules themselves (Table 5).

*Spectral Properties.*—The i.r. spectrum of the present compound shows a band at *ca.* 1 670 $cm^{-1}$, comparable to that of free IMP, which has an absorption at *ca.* 1 675 $cm^{-1}$. It is characteristic of a free uncomplexed CO group. The slight lowering of the CO stretching frequency may be an indication of the hydrogen-bonding interaction involving the exocyclic purine ring atom, O(6). This value is also close to the stretching vibration (1 680 $cm^{-1}$) in the binuclear complex $[\{Cu(IMP)(dpa)(H_2O)\}_2]$,[21] where the purine base is not involved in metal binding. On the other hand, the lowering of CO stretching frequency to *ca.* 1 620 $cm^{-1}$ in $[Cu_4(IMPH_{-1})_2(phen)_4(H_2O)_4]^{2+}$ [35] is a clear indication of the involvement of the carbonyl oxygen in metal co-ordination.

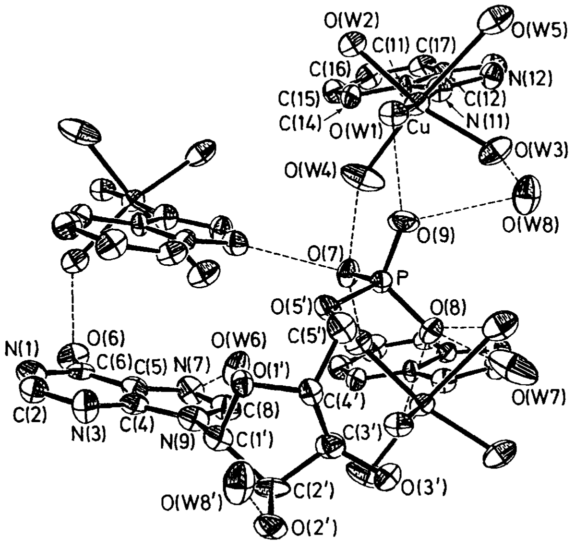

**Figure 2.** A view down *c* of the structure showing the stacking of bzim and the purine base. The sequence repeats by unit translation along *a* (vertical direction). Broken lines indicate hydrogen bonds

## Discussion

The majority of metal–nucleotide complexes structurally characterized contain IMP and the closely related GMP. These nucleotides show two broad types of binding modes in binary system.[1f] Either the co-ordination is only through the atom N(7) of the base, leading to complexes of the type $[M(nucleotide)(H_2O)_5]$, or through both N(7) and the phosphate oxygens resulting in polymeric structures. It is well known that the presence of an additional ligand around the metal strongly influences the binding mode of the nucleotide. As mentioned earlier, solution studies have shown that in metal–nucleotide complexes containing $\pi$-aromatic amines like bipy, dpa, or phen the nucleotide prefers to co-ordinate only through the phosphate oxygens, while the nucleotide base stacks with the ternary ligand instead of binding directly to the metal. *X*-Ray structural studies on metal complexes containing $\pi$-aromatic amines have confirmed the above-mentioned 'phosphate only' mode of binding. The complexes $[\{Cu(3'\text{-}GMP)(phen)(H_2O)\}_2]$,[18] $[\{Cu(IMP)(dpa)(H_2O)\}_2]$,[20,21] and $[\{Cu(AMPH)(bipy)(H_2O)\}_2]^{2+}$ [16] are dimeric with the aromatic amine co-ordinating through the nitrogen donor and the nucleotide bridging the two copper(II) centres through the phosphate oxygens. Furthermore, this mode of binding has also been shown by pyrimidine nucleotides in $[\{Cu(CMP)(dpa)(H_2O)\}_2]$,[19] $[\{Cu(UMP)(dpa)(H_2O)\}_2]$,[17] and $[\{Cd(UMP)(dpa)(H_2O)_2\}_n]$.[19] Though the cadmium(II) complex is polymeric, the metal co-ordinates only to phosphate oxygens. Metal–phosphate binding is also observed in ternary metal complexes with ATP, *viz.* $[\{Cu(ATP)(phen)\}_2]$[36] and $[Zn(ATP)(bipy)]$.[37] It was concluded, therefore, that the 'phosphate-only' binding mode is typical of ternary complexes containing $\pi$-aromatic amines.

The present result differs from those mentioned above. The nucleotide is held in the lattice through hydrogen bonds and stacking interactions without any direct metal interaction.

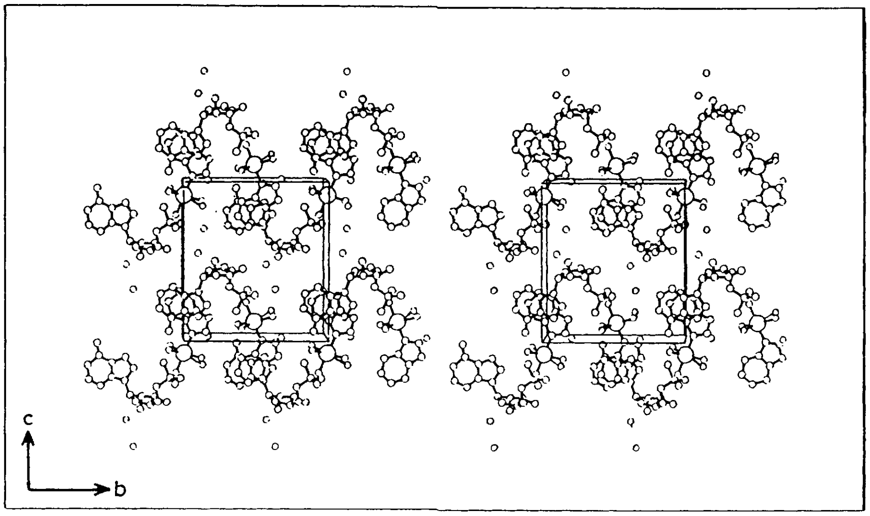

**Figure 3.** Stereoview of the packing of the molecules in the unit cell viewed down *a*

**Table 5.** Possible hydrogen bonds

| D–H···A[a] | Bond/Å D–H | D···A | H···A | Angle/° |
|---|---|---|---|---|
| O(W1)–H(17)···O($9^{I}$) | 0.79 | 2.63 | 1.91 | 169 |
| O(W4)–H(23)···O($7^{I}$) | 0.86 | 2.72 | 1.96 | 147 |
| N(12)[b]···O($7^{II}$) | | 2.66 | | |
| O(W2)–H(18)···O($7^{III}$) | 0.84 | 2.65 | 1.99 | 134 |
| O(W1)–H(17)···O($8^{III}$) | 0.79 | 2.66 | 1.89 | 158 |
| O(W5)–H(25)···O($8^{III}$) | 1.00 | 2.79 | 1.93 | 142 |
| O(W7)–H(28)···O($8^{II}$) | 0.86 | 2.69 | 1.67 | 147 |
| O(W8)–H(31)···O($9^{II}$) | 1.05 | 2.70 | 1.97 | 166 |
| O(W2)–H(19)···O($6^{II}$) | 1.09 | 2.75 | 2.02 | 132 |
| O(W4)–H(23)···O($6^{II}$) | 0.86 | 2.73 | 1.72 | 140 |
| O(W6)–H(27)···N($7^{II}$) | 1.05 | 2.85 | 1.76 | 166 |
| N(1)–H(1)···O($W5^{IV}$) | 0.91 | 2.81 | 1.89 | 147 |
| O(2′)–H(9)···O($W8^{III}$) | 0.97 | 2.85 | 1.96 | 162 |
| O(W7)–H(28)···O($1'^{IV}$) | 0.86 | 2.73 | 1.89 | 163 |
| O(W5)–H(24)···O($W6^{III}$) | 0.87 | 2.88 | 1.94 | 133 |
| O(W3)–H(20)···O($W8^{II}$) | 0.90 | 2.71 | 1.72 | 178 |

[a] D = Donor, A = acceptor. Symmetry codes: I $x,y,z$; II, $\bar{x}, \frac{1}{2} + y, \bar{z}$; III, $x + 1,y,z$; IV, $x,1 + y,z$. [b] Hydrogen atom not located.

There are a few examples of platinum intercalation complexes, [Pt(terpy)Cl][AMP],[38] [Pt(terpy)($SCH_2CH_2OH$)][dCpG],[39] [Pt(phen)(en)][3′-CMP],[40] and [Pt(bipy)(en)][AMP],[41] where again there is no direct metal–nucleotide interaction. In these complexes the planar platinum intercalator stack upon each other in pairs and sandwiched between such pairs are the nuleotide base pairs. The square-planar co-ordination geometry around Pt is satisfied by chelating ligands such as phen, terpy, *etc.* and thus nucleotide co-ordination is rendered redundant. Therefore, these structures are in no way comparable with the present structure.

It is interesting to compare the mode of IMP co-ordination to $Cu^{II}$ in structures containing different π-aromatic amines. Such a comparison should show the influence of the ternary ligand in the complex formation. In the tetranuclear $[Cu_4(IMPH_{-1})_2(phen)_4(H_2O)_4]^{2+}$ [35] complex four ligating sites on the nucleotide, *viz.* N(1), N(7), O(6), and phosphate oxygens, are involved in metal binding. Metal co-ordination at the sites N(1) and O(6) was shown to be a consequence of deprotonation at N(1), which enhances the nucleophilicity of N(1) and O(6). The metal binds at N(7) of the base in the complex $[Cu(IMPH)(bipy)(H_2O)_2]$,[42] as observed in monomeric complexes of the type $[M(nucleotide)(H_2O)_5]$. As pointed out by Bau and co-workers,[20] the absence of phosphate binding in this case is a consequence of protonation of the phosphate group. In $[\{Cu(IMP)(dpa)(H_2O)\}_2]$[20,21] however, in the presence of dpa, the $Cu^{II}$ interacts only with the phosphate group, in agreement with solution studies. On the other hand, the complex $[Cu(IMP)_2(im)_{0.8}(H_2O)_{3.2}]$,[22] which has imidazole instead of benzimidazole in the present case, shows *cis* binding of nucleotides to the Cu–(im) moiety through the N(7) atoms of the bases. These results clearly demonstrate the varied influence of different π-aromatic amines on the mode of IMP co-ordination to $Cu^{II}$. The first two complexes contain IMP groups in their 3− and 1− forms respectively and are, therefore, not entirely relevant to the present discussion. Hence, an understanding of the π-accepting properties of the ternary ligand may be attempted by analysing the results for complexes which contain IMP in its 2− form. The ligand dpa, being a stronger π acceptor compared to im or bzim, imparts discriminating qualities to the metal ion, *i.e.* the metal prefers to bind to the phosphate oxygens rather than to the nitrogen donors of the base. The structural study on the complex with im shows that the $Cu(purine)_2$ moiety still retains the tendency to bind to the oxygen donors in the form of water molecules by partially labilizing the im groups, possibly due to the greater π-accepting property of the purine base compared to the latter. Of the two ligands im and bzim, the latter has greater π-accepting ability than the former. The indirect interaction of phosphate oxygens with the metal through hydrogen bonds with co-ordinating waters in the present structure is probably a reflection of this characteristic of the ligand.

Considering the two ligands bzim and IMP in the present compound, the relevant acidity constants are $pK^{H}_{H(bzim)} = 5.6$[43] and $pK^{H}_{H(IMP)} \approx 6.25$;[1c] hence $\log K^{Cu}_{Cu(bzim)} > \log K^{Cu}_{Cu(IMP)}$. Thus interaction of Cu with bzim is favoured over $IMP^{2-}$ co-ordination. Hence, at pH 6 in solution, $Cu^{2+}$ is predominantly co-ordinated to bzim forming $Cu(bzim)^{2+}$. This species is expected to be hydrolysed to a significant extent at this pH and therefore the dominant species in solution would be $Cu(bzim)(OH)^{+}$. Consequently one could expect the ion pair $[Cu(bzim)(OH)(H_2O)_4]^{+}[IMPH]^{-}$ to crystallize out. The short Cu–O bond (1.955 Å) also appeared to suggest that this co-ordinating atom may be from an $OH^{-}$ group, lending further support to this assumption. Such a possibility, however, is categorically ruled out on the following crystallographic considerations.

(*a*) Similar short distances $[Cu–O(water)_2]$ have also been observed in $[Cu(theo)_2(H_2O)_2][NO_3]_2$[44] [Cu–O 1.948(3) Å] and $[Cu(p\text{-}Pxd\text{-}Gly)(H_2O)]\cdot 3H_2O$ (*p*-Pxd-Gly = 5′-phosphopyridoxylideneglycinate) [Cu–O 1.924(8) Å].[45]

(*b*) All the P–O bond lengths of the phosphate group are normal and there is no evidence for protonation of phosphate in which case one of the P–O bonds would be *ca.* 1.55 Å.[42]

(*c*) All the protons were located unambiguously from the difference electron-density map and it was established that O(W1) was indeed a water oxygen.

In summary, we have in the present structure an unprecedented case of a 6-oxopurine ligand remaining uncomplexed in the compound. Our results show that in the case of ternary systems containing π-aromatic amines, apart from the commonly observed phosphate binding, other modes of co-ordination to the nucleotide are also possible, these being influenced mainly by the π-accepting properties of the ternary ligand. The dominant role of non-bonding interaction in such systems is also clearly brought out. The present result represents an alternative structural type which, perhaps, should be kept in mind when spectral results are interpreted.

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