of the old z axis and also confine rearrangement of ligands to the xy plane. We conclude that rearrangement will and can only occur to the trigonal bipyramid with X apical (B) and that attack by the entering water molecule will be limited by the electron distribution to the equatorial plane, with the same cis-attack symmetry rule as for bipyramid A. This intermediate can lead, therefore, only to *cis*-aquo-X product in the theory. The last possibility, loss of the axial L from the $^4B_2$ state, seems highly improbable as there is no labilization on this axis. If, however, it did occur, it would be expected to give a tetragonal pyramid of high reactivity, with a doubtful urge to rearrange to any trigonal bipyramid. It would therefore react with retention of configuration and would be expected to yield trans product exclusively. We consider it so improbable, however, that we do not entertain it as a real possibility.

We conclude that the VC theory predicts (1) that axial and equatorial ligand loss from the ^4E state lead to the same trigonal bipyramid and therefore give rise to the same product stereochemistry[6] and (2) that equatorial ligand loss from the $^4B_2$ state of $[CrL_5X]^{2+}$ leads eventually only to cis aquo product.

These predictions cannot account for the high proportion of trans product found as a result of equatorial ammonia loss in $[Cr(NH_3)_5F]^{2+}$, and we conclude that the VC theory of the stereochemistry cannot be correct. The author has argued before[7] that the unique features of the stereochemistry of Cr(III) photoreactions likely relate to the vacant t_{2g} orbital in the excited state, which enables bonding of an entering ligand, and that reaction by a concerted mechanism involving a seven-coordinate transition state is the most likely explanation of the stereomobility of the process. A theory along these lines would be most useful.

Registry No. *trans*-$[Cr(en)_2NH_3F]^{2+}$, 58410-71-2; $[Cr(NH_3)_5F]^{2+}$, 65982-64-1; *cis*-$[Cr(en)_2(NH_3)_2]^{3+}$, 66008-06-8.

References and Notes

(1) L. G. Vanquickenborne and A. Ceulemans, *J. Am. Chem. Soc.*, **99**, 2208 (1977).
(2) L. G. Vanquickenborne and A. Ceulemans, *J. Am. Chem. Soc.*, **100**, 475 (1978).
(3) C. F. C. Wong and A. D. Kirk, *Inorg. Chem.*, **16**, 3148 (1977).
(4) A. D. Kirk, L. A. Frederick, and C. F. C. Wong, *Inorg. Chem.*, **18**, 448 (1979).
(5) M. F. Manfrin, D. Sandrini, A. Juris, and M. T. Gandolfi, *Inorg. Chem.*, **17**, 90 (1978).
(6) It should be noted that, for loss of the equatorial ligand from ^4E, the trigonal-bipyramidal intermediate is produced in an excited state for which the symmetry restrictions now require trans attack of the entering ligand. If one accepts the possibility of reaction by the five-coordinate excited-state intermediate, then this explains the trans product from this reaction mode and suggests that the equatorial mode arises from the ^4E state, *inconsistent* with findings of wavelength and temperature dependence in other complexes. The author acknowledges helpful discussions on the theoretical aspects with A. Ceulemans (Koln, 1978).
(7) A. D. Kirk, *Mol. Photochem.*, **5**, 127 (1973).

Department of Chemistry **A. D. Kirk**
University of Victoria
Victoria, B.C., Canada V8W 2Y2

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Relationship of the *styx* Rules to Wade's Rules

Sir:

For simplicity, consider a neutral boron hydride B_pH_{p+q} in which there is one external terminal hydrogen on each boron. The *styx* rules[1,2] were formulated from the electrons of the inner polyhedral surface,[2] neglecting bonds to the outer surface of the external hydrogens, as

$$s + x = q$$

$$s + t = p$$

$$t + y + (q/2) = p$$

and hence are related to the total electron count of the inner surface. Addition of the first equation to the last yields

$$s + t + y + x = p + (q/2)$$

Either side of this equation is recognizable as the number of bonding pairs. Wade's rules[3] then follow upon identification of q values of 2, 4, 6, and 8 with the closo, nido, arachno, and hypho types of boron hydrides, corresponding to the earlier formulation initiated by Stock of B_pH_{p+2}, B_pH_{p+4}, B_pH_{p+6}, and B_pH_{p+8} series and to examples were addition of electrons open the polyhedra.[2]

References and Notes

(1) Eberhardt, W. H.; Crawford, B., Jr.; Lipscomb, W. N. *J. Chem. Phys.* **1954**, *22*, 989.
(2) Lipscomb, W. N. "Boron Hydrides"; W. A. Benjamin: Reading, MA, 1963; pp 47, 53, 115.
(3) Wade, K. *Chem. Commun.* **1971**, 792; "Electron Deficient Compounds"; Nelson: London, 1971; Appleton: New York, 1973. Rudolph, R. W. *Acc. Chem. Res.* **1976**, *9*, 446. Wade, K. *Adv. Inorg. Chem. Radiochem.* **1976**, *18*, 1.

Gibbs Chemical Laboratory **William N. Lipscomb**
Harvard University
Cambridge, Massachusetts 02138

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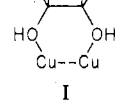
The Reaction Product of Uridine with Dimeric Copper Acetate: Not a Monomer

Sir:

Biological processes which distinguish between ribo- and deoxyribonucleosides frequently involve metal ions.[1] Berger et al.[1] have presented evidence that dimeric copper(II) acetate ($Cu_2(OAc)_4$) in dimethyl sulfoxide (Me_2SO) reacts with ribonucleosides to form a unique type of dimeric complex in which the 2′ and 3′ furanose hydroxyl oxygens interact with each of the Cu atoms as in I. The distance between the O



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atoms is 2.7 Å and that between the Cu atoms in $Cu_2(OAc)_4 \cdot 2H_2O$ is 2.64 Å. Deoxynucleosides which lack analogous hydroxyl groups cannot form such a complex. The validity of this intriguing dimer model has been questioned.[2-4] The principal objection offered in the literature is that the available spectroscopic data can be accommodated by monomeric Cu(II) species.[2,3]

Some important observations reported earlier[1] for Me_2SO solutions of $Cu_2(OAc)_4$ include: a 50% hypochromic effect at ~715 nm upon addition of various ribonucleosides, no spectral change upon addition of pyrimidine deoxynucleosides, and a stoichiometry of one ribonucleoside to one $Cu_2(OAc)_4$ dimer.

Frozen Me_2SO solutions of $Cu_2(OAc)_4$ and ribonucleosides were investigated later by Brun et al.[2] using ESR. These frozen solutions had signals which were attributed to monomeric Cu(II) complexes. Without any experimental justification, it was concluded that monomers must also be formed at ~300 K. The visible spectral changes accompanying the

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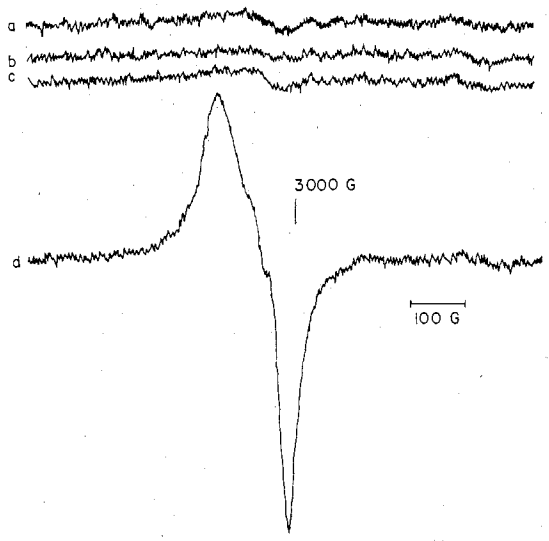

Figure 1. X-Band ESR spectra of Me_2SO solutions (~300 K): a, 1×10^{-3} M $Cu_2(OAc)_4$; b, a plus 1×10^{-3} M uridine; c, a plus 1×10^{-3} M deoxycytidine; d, 2×10^{-3} M $Cu(NO_3)_2$. All solutions were freshly prepared. Solutions a, b, and c do not show the presence of any substantial proportions of monomeric copper(II). Even at higher concentrations of uridine, up to 0.5 M, no increased monomer signal was observed. Addition of comparable amounts of $Cu_2(OAc)_4$, uridine, or a mixture of the two to $Cu(NO_3)_2$ solutions did not affect the $Cu(NO_3)_2$ spectrum. Spectra were obtained on a Varian E-12 ESR spectrometer.

addition of nucleoside were also reinterpreted[3] to suggest the plausibility of monomer formation. The uniqueness of the proposed ribonucleoside–copper dimer complex, the selectivity of the reaction, and the failure of the subsequent studies to account for the one ribonucleoside to one $Cu_2(OAc)_4$ stoichiometry prompted the present investigation.

In Figure 1, we present representative ESR spectra for Me_2SO solutions (at ~300 K) containing either $Cu_2(OAc)_4$ or $Cu(NO_3)_2$. If monomeric species were formed in solutions containing $Cu_2(OAc)_4$ and ribonucleosides, we should observe pronounced ESR signals comparable to those illustrated for $Cu(NO_3)_2$. Neither uridine, which does not coordinate via the base under these conditions,[4] nor deoxycytidine, which contains a potentially coordinating base, causes the appearance of a monomer signal, Figure 1. When the solution is frozen, a somewhat increased monomer signal was observed with $g \simeq 2.2$.

Our magnetic data, Table I, are consistent with the formation of dimeric nucleoside complexes. Because the Cu atoms in $Cu_2(OAc)_4$ are weakly coupled antiferromagnetically, the magnetic moment (per Cu) is only 1.4–1.5 μ_B, as compared to typical values of 1.8–2.0 μ_B (for monomers).[5] If ribonucleosides actually disrupted the dimers completely, the magnetic moment should *increase*. However, when nucleoside and $Cu_2(OAc)_4$ concentrations are comparable, the magnetic moment remains the same, and, at high ribonucleoside concentrations, the magnetic moment actually decreases slightly. At these high concentrations, further reactions take place (vide infra).

Changes we observed in the visible spectrum of $Cu_2(OAc)_4$ on adding ribonucleosides closely matched those reported,[1] Figure 2. We attempted to fit our visible spectral data with various models, and the best results were obtained if we assumed the following reaction

$$Cu_2(OAc)_4 + \text{uridine} \rightleftharpoons Cu_2(OAc)_2(\text{uridine}^{2-}) + 2OAcH$$

The changes in conductivity which accompanied the reaction were much too small to accommodate the formation of acetate ions but were comparable to the changes that we observed when appropriate amounts of acetic acid were added to $Cu_2(OAc)_4$ solutions. These conductivity changes were insufficient for quantitative treatment. Addition of acetic acid also reversed the reaction as required by the stoichiometry. The accuracy of the data is limited because at high nucleoside

Table I. Summary of Spectral and Magnetic Data[a]

salt	Cu:ligand:PS concn ratio	μ, μ_B	ESR	ϵ, M^{-1} cm^{-1} (λ, nm)
		No Ligand		
$Cu_2(OAc)_4$		1.50[c]	w[c]	170 (713)
$Cu(NO_3)_2$		1.94	s	38 (840)
$Cu(NO_3)_2$[b]		1.95	s	
		Uridine		
$Cu_2(OAc)_4$	1:2:0	1.50[c]	w	80 (713)
$Cu_2(OAc)_4$	1:10:0	1.37[c]	w	50 (713)
$Cu(NO_3)_2$	1:10:0	1.82	s	
$Cu(NO_3)_2$	1:10:2	1.47	w	47 (726)
$Cu(NO_3)_2$[b]	1:2:0[d]	1.24	w	49 (692)
$Cu(NO_3)_2$[b]	1:2:0[e]	1.70	s	24 (635)
		D(+)-Galactose		
$Cu_2(OAc)_4$	2:1:0	1.71	w	78 (745)[f]
$Cu_2(OAc)_4$	1:1:0	1.79	w	75 (743)[f]
$Cu_2(OAc)_4$	1:2:0	1.85	w	70 (742)[f]
$Cu_2(OAc)_4$	1:5:0	1.67	w	70 (742)[f]
$Cu_2(OAc)_4$	1:10:0	1.25	w	69 (742)[f]
$Cu(NO_3)_2$[d]	1:2.5:0	1.86	s	
$Cu(NO_3)_2$[c]	1:2.5:2.5	1.39	w	

[a] In Me_2SO except as noted; all values expressed on a per Cu basis; ratios and conditions for the magnetic studies; ESR and visible data for solutions of comparable properties and compositions. Magnetic susceptibilities were determined on 60 MHz instruments at ~32 °C by using Evans's method[9] with 10% benzene serving as the noninteracting reference. ESR spectra are for ~300 K only, with w and s indicating weak and strong signals. [b] Me_2SO–H_2O 50:50 by volume; methyl resonance of *tert*-butyl alcohol as reference. [c] Addition of PS had no effect on these values. [d] Green compound of ref 4. [e] Blue compound of ref 4. [f] For a total [Cu] = 5 mM. For the ratio of 1:100:0, the values were 56 (730), and this value corresponds most closely to the 1:10:0 magnetic measurements since uridine concentration was 0.5 M.

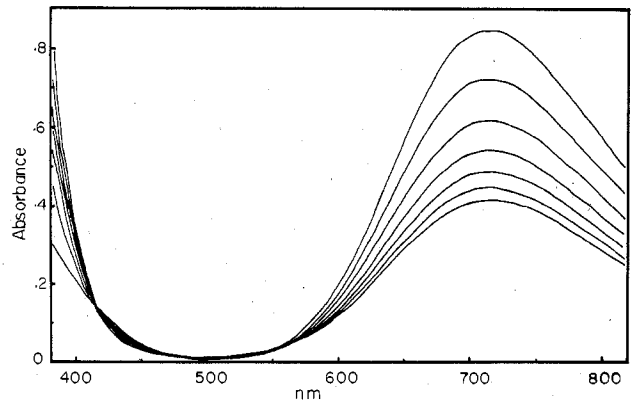

Figure 2. Effect of increasing concentrations of uridine on the visible spectrum of a 2.5×10^{-3} M $Cu_2(OAc)_4$ solution in Me_2SO. The spectra were obtained with 1-cm quartz cuvettes by using a Cary 17 spectrophotometer. The concentrations of uridine in the different solutions (in order of decreasing absorbance around 715 nm) were 0, 4.2×10^{-4}, 8.3×10^{-4}, 1.3×10^{-3}, 1.7×10^{-3}, 2.1×10^{-3}, and 2.5×10^{-3} M, respectively. When the concentration of uridine was increased beyond 2.5×10^{-3} M, the spectrum no longer passed through the isosbestic points at 415 and 485 nm. At these high concentrations the extinction coefficient at 713 nm (per Cu) dropped to ~50 mol^{-1} cm^{-1} from ~80 mol^{-1} cm^{-1} for the presumed $Cu_2(OAc)_2$(uridine^{2-}) compound. For D(+)-galactose, approximately these same extinction coefficients were found, but λ_{max} was ~745 nm at low concentrations and ~730 nm at high concentrations.

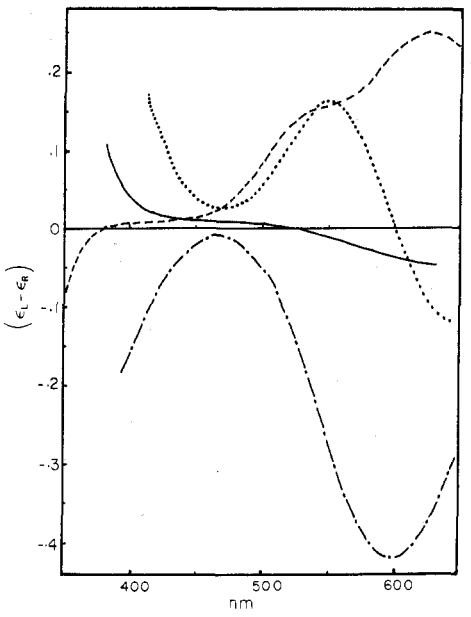

Figure 3. Comparison of the CD spectrum of solutions of $Cu_2(OAc)_4$ and uridine in Me_2SO (—) with those of $Cu^{II}(NO_3)_2$, uridine, and PS in Me_2SO (···), $Cu^{II}(NO_3)_2$ and uridine in 50% Me_2SO–water mixture at pH ~9.5 (-·-·), and $Cu^{II}(NO_3)_2$ and uridine in 50% Me_2SO–water mixture at pH ~12.2 (---). The total concentration of Cu in all solutions was 2.5×10^{-2} M and that of uridine and of PS was 0.1 M. The $(\epsilon_L - \epsilon_R)$ values were calculated for total Cu concentrations. The values would hence be twice as great if expressed in terms of dimers. Spectra were obtained with 1-cm cells on a Cary Model 60 spectropolarimeter fitted with a Model 6002 CD attachment.

concentrations, further reactions take place (see caption for Figure 2).

One of the arguments used to support structure I was the absence of a reaction between monomeric $Cu(NO_3)_2$ and ribonucleosides.[1] However, since OAc^- acts as a base as well as a bridging ligand, we investigated the effects of adding the noncoordinating base Proton Sponge ≡ PS (*N,N,N′,N′*-tetramethyl-1,8-naphthalenediamine from Aldrich) to $Cu(NO_3)_2$ solutions containing ribonucleosides. A reaction was observed when PS was added, and the product is probably at least a dimer, as evidenced from the weak ESR signals and the low magnetic moment (Table I). Furthermore, the visible spectrum of the product was very similar to but not identical with that of the dimer formed from $Cu_2(OAc)_4$. However, at least one ribonucleoside per Cu is needed to prevent precipitation, and the CD spectrum of the product is very different from that of the $Cu_2(OAc)_4$ product, Figure 3. In Figure 3 and Table I, we present CD and magnetic data on a dihydroxy-bridged uridinecopper(II) dimer and a bis(uridine)copper(II) monomer prepared according to the literature.[4] At the pH values used,[4] there is no ESR signal as reported,[4] but the dimer is antiferromagnetic, not diamagnetic. It also has a much more pronounced CD spectrum than that of the $Cu_2(OAc)_4$/uridine product.

Similar studies were performed with the hexose D(+)-galactose. The results, Table I, obtained parallel those described above for uridine. However, the product formed from $Cu_2(OAc)_4$ at lower concentrations of D(+)-galactose, Table I, has a higher magnetic moment than that in the uridine reaction. This result can be explained by using structure I. The O–O distance in D(+)-galactose is 2.81 Å.[6] To accommodate this larger distance, the Cu–Cu bond length might expand, and the antiferromagnetic coupling would be diminished. At low concentrations of galactose, hypochromism is observed, but the λ_{max} in the visible region shifts to ~740 nm. At higher concentrations of sugar, the λ_{max} begins to shift to lower wavelength. At these high concentrations, both uridine and D(+)-galactose products have low magnetic moments. Evidently, in the subsequent species formed, the O–O separation is less important. As found for uridine, the CD spectrum of the Cu_2Ac_4/galactose product is much less intense than that of the $Cu(NO_3)_2$/galactose/PS product.

In summary, all of our data can be accommodated by the essential features of the unique structure proposed earlier.[1] We have established beyond question that monomer products are not formed to a significant extent at ~300 K. The monomer signals observed by Brun et al.[2] are probably an artifact of the freezing process. The weak CD spectra observed for the reaction products of $Cu_2(OAc)_4$ and either uridine or D(+)-galactose suggest a rather different structure for these compounds compared to products formed in the absence of the bridging acetate group. It is indeed likely that the first coordination spheres of the Cu(II) centers in the dimers (or polymers) are very similar and probably contain four strongly bound ligating oxygens. This would account for the similar visible spectra we observed.

At this juncture, we have not established structure I as the only structure consistent with our results and do not feel it is feasible to characterize further the $Cu_2(OAc)_4$ + nucleoside reaction products. Attempts to obtain crystalline materials have not been successful. Our data do not permit us to rule out polymeric copper species but do allow the definite statement that contrary to the most recent suggestions in the literature,[2,3] the products are not monomers. It seems unlikely that structure I has any direct biochemical significance. However, a metal ion in conjunction with another electrophile, such as a hydrogen-bond donor, could selectively interact with ribonucleosides in preference to deoxyribonucleosides. We have demonstrated[7,8] that interligand hydrogen bonding allows simple metal complexes to distinguish between the common nucleosides, and perhaps the distinction between ribo- and deoxyribonucleosides can be made similarly.

Acknowledgment. This study was supported by Grant GM 20544 from the Institute of General Medical Sciences, National Institutes of Health.

Note Added in Proof. In a recent correspondence on Cu nucleoside complexes (Nelson, H. C.; Villa, J. F. *Inorg. Chem.* **1979**, *18*, 1725), several misleading statements were made concerning the literature on metal complexes of nucleic acid constituents. A solid metal deoxynucleoside complex has not only been isolated but also structurally characterized by X-ray crystallography (Sorrell, T.; Epps, L. A.; Kistenmacher, T. J.; Marzilli, L. G. *J. Am. Chem. Soc.* **1977**, *99*, 2173). Solid complexes with the metal bound to the ribose are also known (for a recent review see: Gellert, R. W.; Bau, R. In "Metal Ions in Biological Systems"; Sigel, H., Ed.; Marcel Dekker: New York, 1979; Vol. 8, p 1).

Registry No. $Cu_2(OAc)_4$, 23686-23-9; $Cu(NO_3)_2$, 3251-23-8; uridine, 58-96-8; D-(+)-galactose, 59-23-4; deoxycytidine, 951-77-9.

References and Notes

(1) Berger, N. A.; Tarien, E.; Eichhorn, G. L. *Nature (London), New Biol.* **1972**, *239*, 237–40.
(2) Brun, G.; Goodgame, D. M. L.; Skapski, A. C. *Nature (London)* **1975**, *253*, 127–8.
(3) Kirchner, S. J.; Fernando, Q.; Chvapil, M. *Inorg. Chim. Acta* **1977**, *25*, L45–6.
(4) Chao, Y.-Y. H.; Kearns, D. R. *J. Am. Chem. Soc.* **1977**, *99*, 6425–34.
(5) Massey, A. C. In "Comprehensive Inorganic Chemistry"; Bailar, J. C., Emeleus, H. J., Nyholm, R., Trotman-Dickenson, A. F., Eds.; Pergamon Press: Oxford, 1973; Vol. 5, pp 51–5.
(6) Sheldrick, B. *Acta Crystallogr., Sect. B* **1976**, *32*, 1016–20.
(7) Marzilli, L. G.; Kistenmacher, T. J. *Acc. Chem. Res.* **1977**, *10*, 146–52.
(8) Sorrell, T.; Epps, L. A.; Kistenmacher, T. J.; Marzilli, L. G. *J. Am. Chem. Soc.* **1977**, *99*, 2173–79.
(9) Evans, D. F. *J. Chem. Soc.* **1959**, 2003–5.

Department of Chemistry
The Johns Hopkins University
Baltimore, Maryland 21218

Purush Chalilpoyil
Luigi G. Marzilli*

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