

Figure 1. A computer-generated perspective drawing of the diketone **2**. Hydrogens are omitted for clarity, and no absolute stereochemistry is implied.

observed ($F_o^2 \leq 3\sigma(F_o^2)$) after correction for Lorentz, polarization, and background effects.

The angular dependence of the scattering was eliminated as the diffraction data were converted to normalized structure factors.⁴ Phases were assigned to the 200 largest E values by a multiple solution, weighted tangent formula approach.⁵ The weighted E synthesis from the "best" set of phases showed most of the nonhydrogen atoms. The complete nonhydrogen atom structure was revealed by recycling⁶ this plausible fragment through tangent formula refinement with all E values ≥ 1.00 . Hydrogen atoms were located in difference density syntheses.⁷ Full-matrix least-squares refinement with anisotropic temperature factors for nonhydrogen atoms and isotropic temperature factors for hydrogens have converged to a conventional crystallographic residual of 0.049 for the observed data. Further crystallographic details can be found in the supplemental material.

A perspective drawing of the final x-ray model less hydrogens is given in Figure 1. The diketone **2** has an essentially perpendicular arrangement of a γ -pyrone ring and a cyclohexenone ring. The γ -pyrone ring is planar, with the OCH_3 group rotated to move C(23) H_3 0.125 Å out of the ring plane, away from C(21) H_3 . As expected, the cyclohexenone ring is quite flat, with C(7), C(8), C(9), and C(10) forming a plane. The dihedral angle about the C(8)–C(9) bond is $\sim 5^\circ$. Atom C(6) lies 0.28 Å away from this plane, and C(11) is 0.78 Å away on the same side, so that the entire ring might be described as a very flat boat. The methyl substituents at C(10) and C(6) are cis to each other, as are the substituted γ -pyrone at C(6) and the 1-methylbutenyl fragment at C(11). With the exception of bond lengthening around C(6), presumably due to steric crowding, and bond shortening in the ethyl fragment, due to large thermal motions, all bond distances and angles agree well with generally accepted values.

The boron trifluoride catalyzed rearrangement of cyclic epoxides to ketones has been shown to be a highly stereospecific reaction.⁸ We propose that tridachione (**1**) must have the stereochemistry shown, such that the rearrangement occurred with a suprafacial migration of a proton from C(9) to C(10), causing inversion at C(10). The presence of the epoxide functionality, which gave rise to ^{13}C signals at 60.5 and 54.7 ppm, has been confirmed by a series of reactions which will be reported in detail elsewhere.

Although the α -methoxy- γ -pyrone ring occurs in spectabilin,⁹ a fungal metabolite, the carbon skeleton of **1** has not previously been reported. The carbon skeleton appears to be

derived from a polyketide condensation of seven "propionate" units.

At present, we do not know the original source of **1**. Most opisthobranchs are known to obtain secondary metabolites from dietary sources.¹ However, the presence of functional chloroplasts in *T. diomedea* could provide an alternative source of secondary metabolites. **1** might be synthesized by the chloroplasts alone or by a symbiotic pathway in which the mollusc modifies metabolites produced by the chloroplasts. Unlike those of *Aplysia californica*¹⁰ and some other opisthobranchs, the metabolites of *Tridachella diomedea* were always the same, no matter where the animals were collected in the Gulf of California.

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Supplementary Material Available: Fractional coordinates (Table 1), important bond distances (Table 2), important bond angles (Table 3), and observed and calculated structure factors (Table 4) (10 pages). Ordering information is given on any current masthead page.

References and Notes

- (1) D. J. Faulkner and C. Ireland in "Marine Natural Products Chemistry", D. J. Faulkner and W. H. Fenical, Ed., Plenum Press, New York, N.Y., 1977, p 23.
- (2) E. Marcus and E. Marcus, *Stud. Trop. Oceanogr.*, **6** (II), 154 (1967).
- (3) R. K. Trench, R. W. Greene, and B. G. Bystrom, *J. Cell Biol.*, **42**, 404 (1969).
- (4) A. J. C. Wilson, *Acta Crystallogr.*, **2**, 318 (1949); H. Hauptman and J. Karle, *ACA Monogr.*, **No. 3**, (1953).
- (5) G. Germain, P. Main, and M. M. Woolfson, *Acta Crystallogr., Sect. A*, **27**, 368 (1971).
- (6) J. Karle, *Acta Crystallogr., Sect. B*, **24**, 182 (1968).
- (7) The following library of crystallographic programs was used: C. R. Hubbard, C. O. Quicksall, and R. A. Jacobson, "The Fast Fourier Algorithm and the Programs ALFF, ALFFDP, ALFFT and FRIEDEL", USAEC Report IS-2625, Iowa State University, Institute for Atomic Research, Ames, Iowa, 1971; W. R. Busing, K. O. Martin, and H. A. Levy, "A Fortran Crystallographic Least Squares Program", USAEC Report ORNL-TM-305, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1965; C. Johnson, "ORTEP, A Fortran Thermal-Ellipsoid Plot Program", USAEC Report ORNL-3794, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1965.
- (8) B. N. Blckett, J. M. Coxon, M. P. Hartshorn, and K. E. Richards, *Tetrahedron*, **25**, 4999 (1969).
- (9) K. Kakino, C. A. Hanson and K. L. Rinehart, Jr., *Tetrahedron*, **32**, 217 (1976).
- (10) M. O. Stallard and D. J. Faulkner, *Comp. Biochem. Physiol.*, **49B**, 25 (1974).
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Metal-Metal Interactions in Binuclear Rhodium(I) Complexes Derived from the 7,16-Dihydro-6,8,15,17-tetramethyldibenzo[*b,i*]-[1,4,8,11]tetraazacyclotetradecinato Macrocyclic Ligand

Sir:

Considerable interest exists in polynuclear metal complexes, especially from their potential role in homogenous catalysis,^{1–4} as well as investigating the fundamental nature associated with uncommon metal-metal interactions.^{5–8} In this context, it is

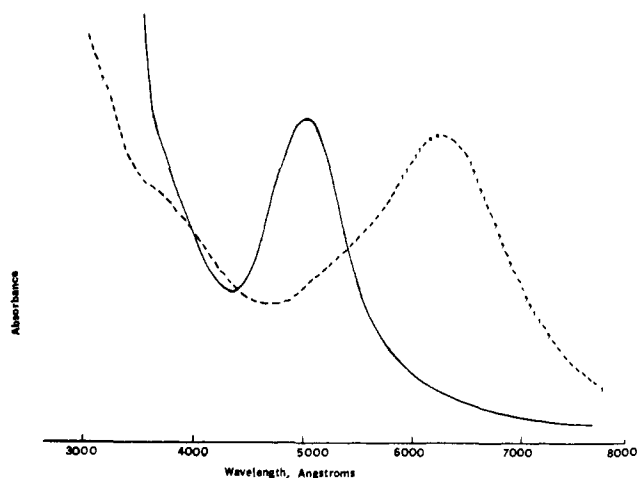
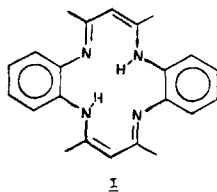


Figure 1. Absorption spectra of $[\text{Rh}(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4]$ (solid line) and of $[\text{Rh}(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]\text{ClO}_4$, solid-state spectrum (dashed line).

highly desirable to fix two or more metal centers in close proximity to enable cooperative interactions of metal centers with substrates. This report describes the syntheses and structural characterizations of binuclear Rh(I) complexes in which a tetraaza macrocyclic ligand serves as the extranuclear bridging unit between two Rh(I) centers, and an unusual intermolecular association producing a linear four-atom chain of Rh(I) atoms. The results of these structural investigations are pertinent to the observations of oligomerization through metal-metal interactions of aryl isocyanide complexes of Rh(I) by Gray and coworkers.⁸

The reaction of $\text{Rh}_2\text{Cl}_2(\text{CO})_4$ with the macrocyclic ligand I (Scheme I) in ethanol produces a black diamagnetic com-



pound of stoichiometry $\text{Rh}_2(\text{C}_{22}\text{H}_{24}\text{N}_4)(\text{CO})_4\text{Cl}_2$ (II). Neutralization with base affords the red molecular species, $\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4$ (III). The mass spectrum of III gave a parent m/e peak corresponding to a molecular weight of 646. The ^1H NMR spectrum confirmed the integrity and symmetry of the ligand: δ 1.77 (12), 4.75 (2), 7.28 ppm (8). The IR spectrum contained strong CO absorptions are 2008 and 2062 cm^{-1} , not far removed from those of the $\text{Rh}_2\text{Cl}_2(\text{CO})_4$.⁹ The remaining portion of the spectrum differed sufficiently from that of other structurally characterized metal complexes of this ligand¹⁰⁻¹³ to conclude that insertion of Rh(I) into the plane

Scheme I

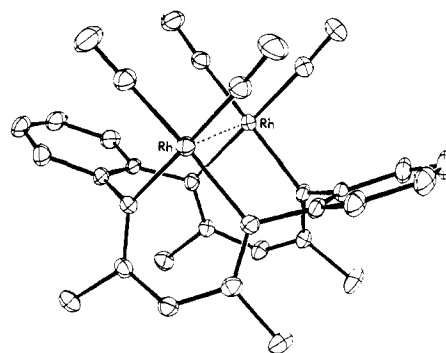
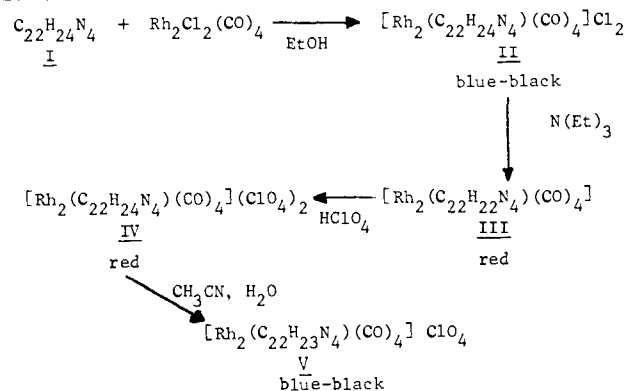


Figure 2. View of the $[\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4]$ molecule. Thermal ellipsoids are drawn at the 20% probability level.

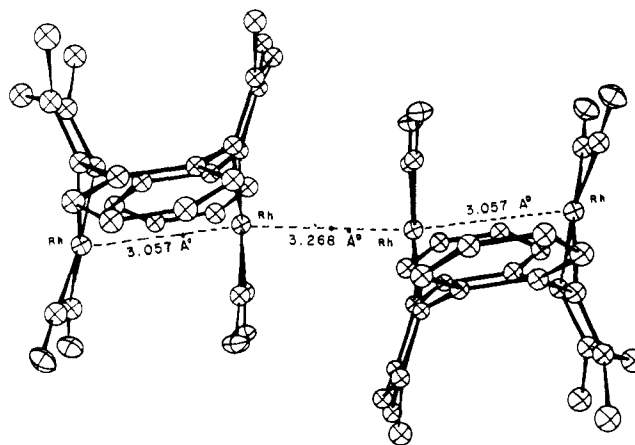


Figure 3. Side view of two $[\text{Rh}_2(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]^+$ cations related by an inversion center illustrating the four-atom Rh(I) chains.

of the ligand had not occurred.

The following observations on the formation and reactivity of III bear emphasis. (1) Monorhodium macrocyclic ligand species are not isolated even when a large excess (fivefold) of the macrocyclic ligand is employed, nor is a monorhodium macrocyclic ligand species formed when $\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4$ (III) is heated with free $\text{C}_{22}\text{H}_{24}\text{N}_4$. (2) The coordinated CO is not displaced by large excesses of triphenylphosphine. (3) Oxidative addition at the Rh(I) center with alkyl halides does not occur. Rather, alkylation at the methine carbon of the 2,4-pentanediiimino rings takes place. Similarly, protonation occurs at the methine carbon atom and not the Rh(I) center as observed for other Rh(I) complexes.

Acidification of this complex with an excess of perchloric acid produced a cherry-red compound, $[\text{Rh}_2(\text{C}_{22}\text{H}_{24}\text{N}_4)(\text{CO})_4](\text{ClO}_4)_2$ (IV). The IR spectrum contained a peak at 1650 cm^{-1} characteristic of isolated imine functions indicating protonation of a methine carbon atom. The NMR spectrum was consistent with this interpretation: δ 2.32 (12), 4.27 (4), and 7.2-7.8 ppm (8). Dissolution of this compound in acetonitrile, followed by precipitation with water, yields the blue-black monoprotonated complex, $[\text{Rh}_2(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]\text{ClO}_4$ (V). The IR spectrum of this complex contained absorptions at 1650 and 1530 cm^{-1} indicating the presence of both protonated and nonprotonated 2,4-pentanediiimino chelate rings. The dramatic shifts in the absorption spectra maxima on going from solution to the solid state (Figure 1) suggested fundamental differences in structure in the two states.

The x-ray structure analysis of $\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4$ was undertaken to make an unequivocal assignment among the various structural possibilities envisaged, all consistent with accumulated physical evidence. Details of the structure of $[\text{Rh}(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]\text{ClO}_4$ (V) were needed for a definitive assessment on the nature of the solid-state interactions.¹⁴

The essential features of $\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4$ (III) can be summarized as follows (see Figure 2). (1) The ligand has an extremely warped conformation (via twisting about the C-N bonds of the five-membered chelate rings such that the nitrogen atom lone pairs are directed almost normal to the N_4 plane). It differs dramatically from the free ligand or any of its metal complexes structurally characterized to date.¹¹ (2) The twisted ligand conformation allows two Rh(I) atoms to coordinate to the macrocyclic ligand, each Rh(I) bound to one of the 2,4-pentanediminato chelate rings.¹² (3) The cofacial arrangement of the dimer leads to an eclipsed arrangement of the coordination dimer. (4) The Rh-Rh separation of 3.086 Å is indicative of weak bonding interaction. (5) The average Rh-N and Rh-C distances are 2.071 (4) and 1.864 (6) Å, respectively.

The structure of $[\text{Rh}_2(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]\text{ClO}_4$ (V) is similar to that of $\text{Rh}(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4$ (III) but has a number of important differences. Protonation at the methine carbon has produced chelates with longer Rh-N bonds, 2.11 (1) Å, on the protonated side and a slightly shorter Rh-N bonds on the other side, 2.05 (1) Å. A slight shortening of the intramolecular Rh-Rh distance to 3.057 (3) Å is observed. Most importantly, the $[\text{Rh}_2(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]^+$ cations are located near a crystallographic inversion center producing four-atom Rh(I) chains comprised of two $[\text{Rh}_2\text{LH}(\text{CO})_4]^+$ units¹⁵ with closest intermolecular Rh-Rh contacts of 3.268 (4) Å. This solid-state interaction accounts for the pronounced color differences between the solution and solid-state species (Figure 3). A closely related structure has recently been found for the platinum compound "cis-diammineplatinum α -pyridone blue" which contains four-atom chains of Pt(II) ions. The Pt(II) ions bridged by the α -pyridone are separated by 2.779 Å; the bridging units are related by a crystallographic inversion center yielding Pt(II)-Pt(II) distances of 2.885 Å between dimers.¹⁶

The complete insolubility of the blue-black dichloride salt, $[\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4]\text{Cl}_2$ (II) and the similarity of its infrared and electronic spectra to those of the monoprotonated species obtained from solid-state spectra strongly indicate an extended linear arrangement of Rh(I) atoms in this structure as well. Intramolecular steric repulsions between carbonyl groups and the methyl groups of the macrocyclic ligand are apparent in Figure 3 and probably account for the existence of polymorphs of this compound.¹⁷

The structure of a porphyrinbis[dicarbonylrhodium(I)] complex has recently been reported^{18,19} but differs in the important respect that the Rh(I) atoms are on opposite sides of the porphyrin plane. The Rh-Rh separation of 3.094 Å and other bond parameters about the Rh atoms do not differ appreciably from the parameters reported herein. The possibility of protonating the porphyrin ligand to alter its electronic structure or the possibility of extended Rh-Rh interactions are less likely.

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References and Notes

- J. B. Keister and J. R. Shapley, *J. Am. Chem. Soc.*, **98**, 1056 (1976), and references cited therein.
- O. Cambino, R. P. Ferrar, M. Chinone, and G. A. Vaglio, *Inorg. Chim. Acta*, **12**, 155 (1975), and references cited therein.
- S. A. R. Knox, J. W. Koepke, M. A. Andres, and H. D. Kaesz, *J. Am. Chem. Soc.*, **97**, 3942 (1975).
- V. W. Day, S. S. Abdel-Meguid, S. Dabestan, M. G. Thomas, W. R. Pretzer, and E. L. Muertteries, *J. Am. Chem. Soc.*, **98**, 8289 (1976), and references cited therein.
- A. H. Reis, Jr., V. S. Hagley, S. W. Peterson, *J. Am. Chem. Soc.*, **99**, 4186 (1977).
- H. Isci and W. R. Mason, *Inorg. Chem.*, **13**, 1175 (1974).
- K. Krogmann, *Angew. Chem., Int. Ed. Engl.*, **8**, 35 (1969).
- K. R. Mann, J. G. Gordon II, and H. B. Gray, *J. Am. Chem. Soc.*, **97**, 3553 (1975), and references cited therein.
- D. Benlian and M. Bigorgne, *Bull. Soc. Chim. Fr.*, 1583 (1963); G. Winkhaus and H. Singer, *Chem. Ber.*, **99**, 11 (1966).
- W. H. Woodruff, R. W. Pastor, and J. C. Dabrowiak, *J. Am. Chem. Soc.*, **98**, 7999 (1976).
- (a) V. L. Goedken, J. J. Pluth, S.-M. Peng, and B. Bursten, *J. Am. Chem. Soc.*, **98**, 8014 (1976); (b) M. C. Weiss, B. Bursten, S.-M. Peng, and V. L. Goedken, *J. Am. Chem. Soc.*, **98**, 8021 (1976).
- A similar mode of coordination has been proposed for tungsten and molybdenum complexes of the composition $\text{M}(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4$. Only one metal is coordinated per ligand and metal-metal interactions are absent. L. G. Bell and J. C. Dabrowiak, *J. Chem. Soc., Chem. Commun.* 512 (1975).
- V. L. Goedken, S.-M. Peng, J. Molin-Norris, and Y.-A. Park, *J. Am. Chem. Soc.*, **98**, 8391 (1976).
- Crystal data for $\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4$: $M = 646$; triclinic, $\overline{P}1$; $a = 10.385$ (2), $b = 11.003$ (2), $c = 12.022$ (1) Å; $\alpha = 111.34$ (1), $\beta = 94.87$ (1), $\gamma = 95.28$ (1)°; $U = 1263.7$ Å³; $D_m = 1.70$, $D_c = 1.67$ g cm⁻³; and $Z = 2$. Crystal data for $[\text{Rh}_2(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]\text{ClO}_4 \cdot \text{C}_7\text{H}_8$: $M = 838.5$; monoclinic, $C2/m$; $a = 17.439$ (8), $b = 18.480$ (9), $c = 12.176$ (8) Å; $\beta = 113.39$ (5)°; $U = 3601.4$ Å³; $D_m = 1.59$, $D_c = 1.55$ g cm⁻³; and $Z = 4$. Intensity data for both structures were collected on an automated diffractometer and the structures solved by Patterson and Fourier techniques and refined by full-matrix least-squares analysis varying positional and anisotropic thermal parameters for nonhydrogen atoms and including hydrogen atoms as fixed contributions. At convergence conventional and weighted R values for $\text{Rh}_2(\text{C}_{22}\text{H}_{22}\text{N}_4)(\text{CO})_4$ were 4.62 and 6.30%, respectively, for 5302 independent reflections with $|F_s| > 3\sigma(F)$. The refinement of $[\text{Rh}_2(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4]\text{ClO}_4 \cdot \text{C}_7\text{H}_8$ was considerably less satisfactory because of crystal decomposition during data collection, unusually rapid decrease of intensity data as a function of θ , and severe disorder of both the perchlorate anion and the solvate toluene molecule. At convergence conventional and weighted R values were 6.6 and 7.5%, respectively, for 1259 independent reflections with $|F_s| > 3\sigma(F)$.
- The nearest Rh(I)-Rh(I) distance between Rh(I) atoms outside the four chains is 7.801 Å. For the molecular species, $\text{Rh}_2(\text{C}_{22}\text{H}_{23}\text{N}_4)(\text{CO})_4$, the closest approach of noninteracting Rh(I) atoms is 4.982 Å.
- J. K. Barton, H. N. Rabinavitz, D. J. Szalda, and S. J. Lippard, *J. Am. Chem. Soc.*, **99**, 2827 (1977).
- Three different polymorphs of $\text{Rh}_2(\text{C}_{22}\text{H}_{24}\text{N}_4)(\text{CO})_4\text{Cl}_2$ have been isolated. Two are blue-black in color, and are presumed to contain a linear arrangement of Rh atoms; they differ in the nature of the fine structure of the carbonyl region (2100-2000 cm⁻¹) of the infrared spectra. The third polymorph is orange and is assumed to be monomeric on the basis of its solubility and the similarity of its electronic spectrum with that of the orange-red perchlorate salt. The orange and blue-black forms are interconvertible in Nujol mulls. Subjecting the monomeric form to high pressures produces a color change from orange to blue-black with corresponding changes occurring in the IR spectrum. The reverse process, although requiring hours to days, occurs when the pressure is released.
- A. Takemak and Y. Sasada, *Acta Crystallogr., Sect. B*, **1**, 1 (1975).
- For reactivities of related porphyrin complexes, see H. Ogoshi, T. Omura, and Z. Yoshida, *J. Am. Chem. Soc.*, **95**, 1966 (1973); Z. Yoshida, H. Ogoshi, T. Omura, E. Watanabe, and T. Kurosake, *Tetrahedron Lett.*, **No. 11**, 1077 (1972); A. Takenaka, Y. Sasada, T. Omura, H. Ogoshi, and Y. Yoshida, *J. Chem. Soc., Chem. Commun.*, 792 (1973).

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Unusual Reactivity of Trifluoroacetyl Peptide Chloromethyl Ketones with Pancreatic Elastase

Sir:

In the course of a recent investigation,¹ it was found that trifluoroacetyl peptides (TFA-peptides) were much more potent reversible inhibitors of elastase than the corresponding acetylated ones (Ac-peptides). This prompted us to study trifluoroacetyl peptide chloromethyl ketones (TFA-peptide-CMK), first in the hope of getting potent irreversible inhibitors of elastase²⁻⁴ which might be useful therapeutic agents, and second to permit the use of ¹⁹F NMR for investigating the interactions of these peptides with the enzyme.

The compounds listed in Table I were prepared as follows. Z-Ala-CH₂Cl was obtained by reacting Z-Ala-CHN₂ with anhydrous HCl.² Deblocking of this compound was performed