Further studies of the chemistry of **1** are in progress.

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**Registry No. 1**, 88180-40-9; **4**, 88180-41-0; **7**, 26537-68-8; **7** alcohol derivative, 4687-23-4; **8**, 131-76-0; **9**, 480-90-0; **10**, 38846-64-9; **11**, 536-74-3; ethyl phenoxyacetate, 2555-49-9.

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# Bifunctional Activation of $CO_2$: A Case Where the Basic and Acidic Sites Are Not Held in the Same Structure

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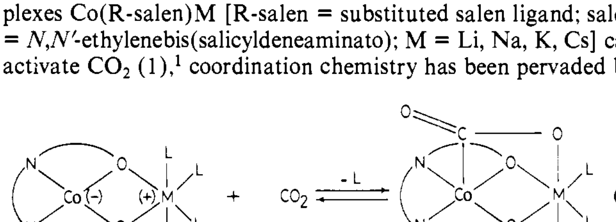
Since the discovery by C. Floriani that the bifunctional complexes Co(R-salen)M [R-salen = substituted salen ligand; salen = *N*,*N'*-ethylenebis(salicyldeneaminato); M = Li, Na, K, Cs] can activate $CO_2$ (1),[1] coordination chemistry has been pervaded by intense efforts to find acidic–basic metal systems capable of promoting $CO_2$. Unfortunately, the R-salen complexes are so far unique examples of this fascinating chemistry.



(1)

We were intrigued by the possibility that $CO_2$ could be activated also by bifunctional metal systems that do not fulfil the limiting requirement of holding the basic and acidic centers in the same structure.

This communication presents the reactions of $CO_2$ with the low-valent cobalt or rhodium complexes $(np_3)CoH$ (**1**)[2] and $(np_3)RhH$ (**2**)[3] [$np_3$ = tris(2-(diphenylphosphino)ethyl)amine] in the presence of a solvated or complexed Lewis acid such as the sodium ion.

On bubbling of $CO_2$ at room temperature into a tetrahydrofuran solution of **1**, no reaction is observed even for long reaction time (24 h), the starting complex being quantitatively precipitated by addition of a solvent such as *n*-butyl ether.

By contrast, on addition of a tetrahydrofuran solution of $NaBPh_4$ to a solution of **1** under $CO_2$ atmosphere, a rapid reaction takes place and the original red-orange color changes to brown-green. The solution turns red-brown within 1 h, indicating the completion of the reaction. Addition of 1-butanol to the reaction mixture and partial evaporation of the solvent cause the precipitation of red crystals of the carbonyl complex $[(np_3)Co(CO)]BPh_4$ (**3**),[2] which optionally can be filtered off. On further concentration the precipitation of the carbonyl complex is accompanied by that of pale violet crystals of a compound that analyzes as $[(np_3{=}O)Co](BPh_4)_2$ (**4**) [$np_3{=}O$ = $O{=}PPh_2CH_2CH_2N(CH_2CH_2PPh_2)_2$] ($\mu_{eff}$ = 4.35 $\mu_B$; 1140 $cm^{-1}$ P=O stretching). Both compounds **3** and **4** can be isolated as pure samples, each of them with yields varying between 40% and 50%.

The transformation of **1** into **3** (yield 50%) is more easily obtained if the sodium ions are complexes by a crown ether like dicycloesano-18-crown-6 ($C_{20}H_{36}O_6$) before being reacted with **1** and $CO_2$. In this case it is sufficient to bubble $CO_2$ into the reaction mixture for a few minutes to have a complete reaction. Furthermore, the color of the solution changes directly from red-orange to red without assuming the initial green tinge. The sodium ions can be quantitatively collected as the crown ether complex with one tetraphenylborate counterion, whereas a minor amount of **4** (yield 5%) is formed.

It is noteworthy that $CO_2$ does not react at all with **1** in the presence of $NBu_4BPh_4$.

Analogously to **1**, a tetrahydrofuran suspension of the rhodium complex **2** reacts within a few seconds with $CO_2$ only in the presence of sodium ions to give the novel yellow-green diamagnetic complex $[(np_3)Rh(CO)]BPh_4$ (**5**) (yield 50%; 1990 $cm^{-1}$ CO stretching).

In the attempt at understanding these reactions and building up a possible mechanism, the following experimental pieces of information are noteworthy. (a) The complex $(np_3)CoH$ is known to react with $CO_2$-like molecules such as RNCO, RNCS, and $CS_2$ to give the corresponding $\eta^2$-complexes $(np_3)Co(\eta^2\text{-}CXY)$ (CXY = heteroallene).[4] Analogously, the $(np_3)RhH$ complex has been found to react with $CS_2$ to yield an $\eta^2$-$CS_2$ complex.[5] (b) At present no definitive conclusions have been reached about the role played by the Co–H hydrogen in these reactions. By analogy with the isoelectronic complexes $[(np_3)NiH]BPh_4$, which can react with CO to give the nickel(0) complex $[(Hnp_3)Ni(CO)]BPh_4$,[6] and $Co(CO)_4H$, which dissociates according to the equation $Co(CO)_4H \rightleftharpoons Co(CO)_4^- + H^+$,[7] we could suggest that an equilibrium of the type $(np_3)CoH \rightleftharpoons (np_3)Co^- + H^+$ may be operating.[8] However, other conceivable pathways such as that involving a preliminary reaction between the Co–H moiety and an heteroallene molecule, cannot be excluded. (c) Dicycloesano-18-crown-6 forms sodium complexes without saturating the coordination sphere of the alkali metal. Other coligands such as water molecules can coordinate sodium.[10] (d) The formation of the complex (triphos)Ni(CO) and a [(triphos=O)Ni] species [triphos = 1,1,1-tris((diphenylphosphino)methyl)ethane] by reaction of $CO_2$ with the (triphos)Ni(0) moiety has been recently suggested to proceed through the intermolecular attack by a phosphorus atom from coordinated triphos on the $CO_2$ molecule of the intermediate species $(triphos)Ni(CO_2)$.[11]

In absence of a detailed mechanistic study the stepwise pathway (2) may be proposed for the reaction of **1** with $CO_2$ in the presence of sodium ions. A similar pathway can be proposed also for the reaction with the rhodium derivative, the only difference being the absence of the corresponding $np_3{=}O$ complex.

Concerning the formation of the intermediate $\eta^1$-$CO_2$ adduct, the presence of the sodium cations seems essential for anchoring the $CO_2$ molecule, which then may be thought of as being attacked by the $(np_3)Co$ fragment. It is well-known, in fact, that $\eta^1$-$CO_2$ coordination is attainable when the metal atom is electronically

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(8) Recent experimental and theoretical studies on the chemistry of **1** suggest that, depending on the reaction conditions, this hydride complex is a potential releaser of hydridic hydrogen, atomic hydrogen, or proton giving rise to the moieties $(np_3)Co^+$, $(np_3)Co\bullet$, and $(np_3)Co^-$, respectively.[9] The former moiety has been isolated as $BPh_4^-$ or $BF_4^-$ salts and does not react with $CO_2$ and related heteroallene molecules, whereas the radical moiety could explain the formation of the paramagnetic $\eta^2$-heteroallene complexes.[4] The $d^{10}$ fragment $(np_3)Co^-$, which is isoelectronic with the trigonal-pyrimidal complex $(np_3)Ni$,[2] should have also the same geometry. In this case the lone pair directed toward the unoccupied site of the bipyramid could favor a C-coordination of the X=C=Y molecules (X, Y = O, S, NPh), which are electrophilic at the central carbon atom.

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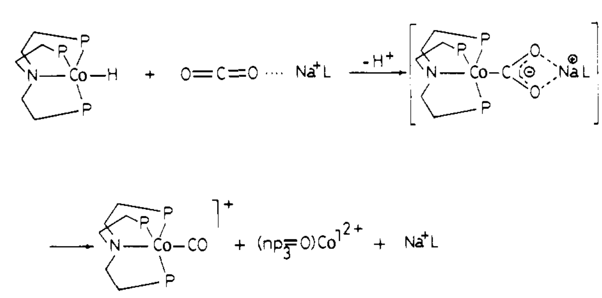

(2)

saturated by its coligands and the fragment has a free coordination site.[12] Nonetheless the initial approach of the metal fragment and $CO_2$ may be difficult and the reaction may be greatly facilitated if $CO_2$ is kept in place by a second function having ionic character.

Unusual features of the reactions reported in this paper are the mild conditions required to activate $CO_2$ and the good yields and rates. Furthermore the present experimental results suggest that a new and perhaps general strategy for $CO_2$ activation could be pursued in coordination and organometallic chemistry. So far, in fact, the major part of the chemical speculation has been focused mainly on basic systems, thus neglecting the role that acidic species could have. The acidic center in bifunctional systems could be indeed responsible of the initial promotion of $CO_2$. Its contribution to stabilize the eventual $CO_2$ adduct or to function as oxygen acceptor will depend then on the particular chemical system. A reconsideration in this light of many metal–$CO_2$ reactions could reveal how often the presence of Lewis acids in the reaction mixture has been misunderstood.

Current studies are under way to investigate the reactivity of $CO_2$ toward nucleophilic complexes in the presence of different types of acidic species.

**Acknowledgment.** Thanks are due to Dr. C. Mealli for helpful discussion.

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[12] (a) For a comprehensive description and reference list of reactions of $CO_2$ with transition-metal complexes, see: Sneeden, R. P. A. "Comprehensive Organometallic Chemistry"; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon Press: Oxford, 1982; Vol. 8, p 255. (b) Mealli, C.; Hoffmann, R.; Stockis, A. *Inorg. Chem.* **1984**, *23*, 56. Calabrese, J. C.; Herskovitz, T.; Kinney, J. B. *J. Am. Chem. Soc.* **1983**, *105*, 5914.

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# Synthesis of Stereoselectively Labeled [9-$^2$H,$^3$H]Chorismate and the Stereochemical Course of 5-Enolpyruvoylshikimate-3-phosphate Synthetase

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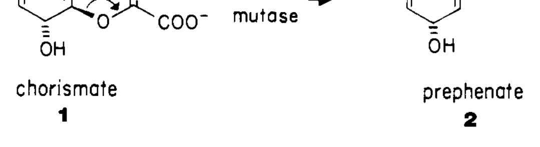
The 3,3-sigmatropic shift of chorismate (**1**) to prephenate (**2**)



chorismate
**1**

prephenate
**2**

is perhaps the only example of a pericyclic reaction in primary metabolism. The nonenzymic reaction occurs smoothly at 60 °C in neutral aqueous solution, and the enzyme chorismate mutase effects a rate acceleration of (2 × 10$^6$)-fold at 37 °C.[2] One of the most basic questions concerning this enzyme-catalyzed Claisen rearrangement is whether the reaction involves a chair or a boat transition state, and to answer this question we required isotopically labeled chorismate in which the *E* and *Z* hydrogens at carbon 9 of **1** were stereochemically distinguished. We report here the synthesis of [9-$^2$H,$^3$H]chorismic acid in which the tritium label is stereoselectively located, and we report the independent stereochemical determination of the tritium position. This work not only yields labeled chorismate suitable for the evaluation of the stereochemical course of the chorismate mutase reaction[3] but also provides information about the stereochemical events in the enzymic reaction used to generate the labeled chorismate: that catalyzed by 5-enolpyruvoylshikimate-3-phosphate synthetase.

Specifically labeled chorismate was synthesized by the condensation of shikimate 3-phosphate (**3**) with specifically labeled phosphoenolypyruvate (**4**) catalyzed by 5-enolpyruvoylshikimate-3-phosphate synthetase. The accepted mechanism for this reaction[4–6] involves the addition-elimination sequence shown in Scheme I. Since carbon 3 of the enolpyruvate moiety transiently becomes a methyl group and methyl group rotation is fast with respect to the chemical steps leading to and from this intermediate, use of specifically monodeuterated **4** leads to a sample of 5-enolpyruvoylshikimate-3-phosphate (**5**) having deuterium equally at *both* the *E* and *Z* positions. We have shown, however, that the synthetase reaction is subject to a kinetic isotope effect in both addition and elimination steps,[6] so if a stereospecific *doubly labeled* sample of phospho[3-$^2$H,$^3$H]enolpyruvate (**6**) is used as substrate,[7] the kinetic isotope effect should result in preferential retention of the heavy isotopic labels. Since, however, tritium is used as a *trace* label whereas deuterium is used *stoichiometrically*, the product **5** that derives from **6** will contain (in the bulk) deuterium randomly in both *E* and *Z* positions yet (for those few molecules that contain tritium) tritium will be preferentially *E* or *Z*.[12] This consequence is illustrated in Scheme II.

To determine whether the tritium label at carbon 9 of chorismate (derived from the doubly labeled sample of **5**) is mainly *E* or *Z*, the stereoanalytical sequence shown in Scheme III was followed. Doubly labeled chorismic acid (prepared[13] from a stereospecific doubly labeled sample of **6**) was dissolved in di-

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[7] The doubly labeled samples of phosphoenolpyruvate were made either from [1-$^3$H]glucose (using phosphoglucose isomerase–$D_2O$) or from [1-$^3$H]-mannose (using phosphomannose isomerase–$D_2O$), by modification of the method of Cohn et al.[8] The configuration and stereochemical integrity of these samples were confirmed by conversion to lactate using pyruvate kinase–ADP[9] plus lactate dehydrogenase–NADH. The resulting lactate samples were subjected to Kuhn–Roth oxidation to acetate, followed by chiral methyl analysis.[10] The *F* values[11] for the acetate samples so derived from (*Z*)- and from (*E*)-[3-$^2$H,$^3$H]phosphoenolpyruvate were 0.30 (sample from [1-$^3$H]-glucose) and 0.66 (sample from [1-$^3$H]mannose), respectively.

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[12] The deuterium kinetic isotope effect in the synthetase reaction is about 2 (at pH 6.25) to nearly 3 (at pH 10), so the tritium in the enolpyruvoylshikimate phosphate will be located *E* (or *Z*) in 2:1–3:1 ratio.

[13] A partially purified preparation of 5-enolpyruvoylshikimate-3-phosphate synthetase[6] was used at pH 7.4. To avoid scrambling and loss of the isotopic labels[4–6] the reaction was stopped after <15% of the doubly labeled phospho[3-$^2$H,$^3$H]enolpyruvate had been converted into product. After purification by ion-exchange chromatography, the [9-$^2$H,$^3$H]-5-enolpyruvoylshikimate-3-phosphate was converted into [9-$^2$H,$^3$H]chorismate using chorismate synthetase.[14]

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