

## Kinetics and Equilibria of Dioxygen Binding to a Vacant Site in Cobalt(II) Complexes with Pentadentate Ligands

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Here we show that dioxygen binding to vacant metal ion sites proceeds at rapid rates, with very low enthalpic barriers but negative activation entropies; the rates are relatively insensitive to the electronic structure of the other ligands bound to the metal. While these properties are shared by vacant sites exposed to noncoordinating solvents and by those having sites protected from solvent, the latter react substantially more rapidly. The oxygenation of cobalt(II) complexes with pentadentate Schiff base ligands dissolved in the noncoordinating solvent acetone has been studied. For nonbridged complexes, reversible formation of 1:1 adducts with O<sub>2</sub> was observed only at low temperatures (from -75 to -40 °C for acetylacetone derivatives and from -75 to -20 °C for salicylaldehyde derivatives), whereas the oxygenation of the corresponding lacunar species is reversible at room temperature. The dioxygen affinity of the salicylaldehyde derivative (CoSalMeDPT) (0.024 Torr<sup>-1</sup> at -39 °C) is significantly smaller than that of the analogous unbridged and *p*-xylene-bridged acetylacetone derivatives (>5 Torr<sup>-1</sup> and 1.8 Torr<sup>-1</sup> at -40 °C, respectively), presumably because of the lower electron-donating ability of the ligand. The dynamics of O<sub>2</sub> binding to a vacant cobalt(II) coordination site proved to be fast (on the order of 10<sup>6</sup> M<sup>-1</sup> s<sup>-1</sup> for unbridged complexes and up to 10<sup>8</sup> M<sup>-1</sup> s<sup>-1</sup> for the bridged ones), due to an extremely low activation barrier (1–3 kcal/mol for both unbridged complexes). The differences in the electronic structures of the ligands is reflected primarily in their O<sub>2</sub> dissociation rates, while steric effects produce significant differences in O<sub>2</sub> binding rates.

### Introduction

The ability of certain cobalt(II) complexes to bind dioxygen reversibly was discovered decades ago.<sup>1</sup> Since then, many cobalt(II) dioxygen carriers have been discovered,<sup>2</sup> some of them having properties which make them good candidates for industrial and/or medicinal applications. While efforts have been made to synthesize new cobalt(II) oxygen carriers and characterize their dioxygen affinities, the dynamics of the dioxygen-binding process have not been studied adequately. In most of the limited number of publications devoted to this subject,<sup>3–5</sup> the authors have found that the dissociation from the cobalt(II) of a coordinated solvent or ligand molecule is, in fact, the rate-determining step in the dioxygen binding process. In other words, the observed rate constants and activation parameters correspond to the dissociation of a ligand (usually

water) from the cobalt(II) compound. Not surprisingly, the binding rates for the synthetic cobalt(II) complexes were found to be slow when compared to natural dioxygen carriers, the observed second-order rate constants falling in the range 10<sup>4</sup>–10<sup>6</sup> M<sup>-1</sup> s<sup>-1</sup>.<sup>3</sup> The O<sub>2</sub> binding rates of hemoglobin and myoglobin are  $k_{\text{obs}} \approx 10^8$  M<sup>-1</sup> s<sup>-1</sup>.<sup>3,6</sup> The fastest reactions observed for synthetic cobalt(II) compounds ( $k_{\text{obs}} \approx 10^7$  M<sup>-1</sup> s<sup>-1</sup>) are those for macrocyclic complexes<sup>5</sup> which, because of their strong equatorial ligand fields, have relatively labile axial water molecules.<sup>7</sup> As expected for dissociative processes, relatively large activation enthalpies are responsible for the slow rates, while the activation entropies are positive and favorable for reaction.<sup>3,4</sup>

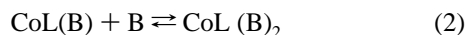
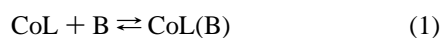
In order to determine the dynamics of the elemental process of dioxygen binding to a cobalt(II) moiety, at least one coordination site on the cobalt(II) ion must be vacant prior to the O<sub>2</sub> binding process. It is also believed that the remaining five cobalt(II) coordination sites (four equatorial and one axial) must be occupied by strong electron donors in order to facilitate efficient dioxygen binding.<sup>2</sup> The dominant traditional approach in the design of cobalt(II) dioxygen carriers has been the use of tetradentate equatorial ligands, to provide the four equatorial donors, in the presence of an excess of a monodentate nitrogen base, the latter serving as the axial ligand. This approach usually fails to provide a vacant coordination site, because 6-coordinate

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species can be formed in the presence of excess base:<sup>8-10</sup>



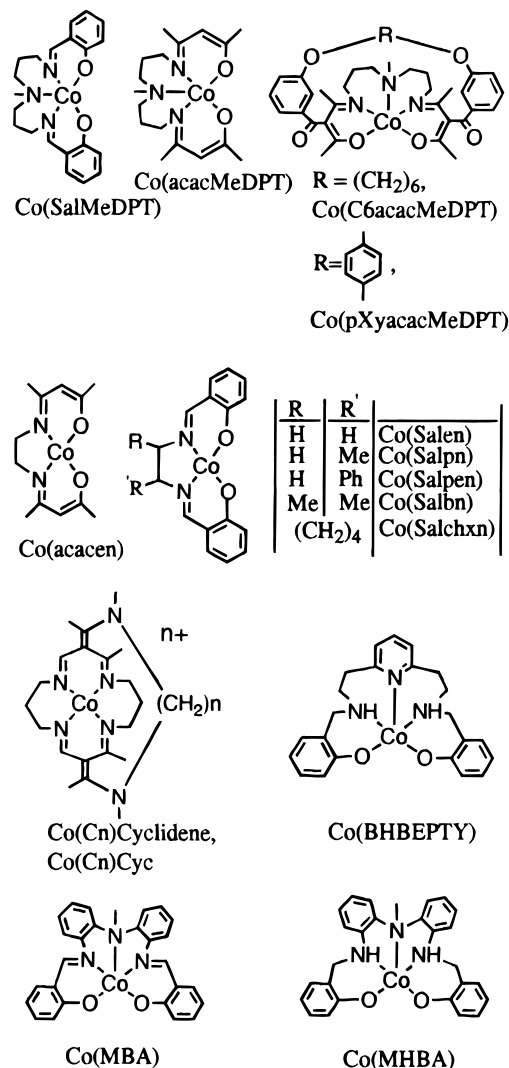
For example, slow rates of dioxygen binding ( $k = 10^2\text{--}10^5 \text{ M}^{-1} \text{ s}^{-1}$ ) were measured electrochemically for Co(Salen) derivatives in the presence of pyridine.<sup>11</sup> Apparently, dissociation of the sixth ligand is rate determining in that system.

Several methods have been suggested for the suppression or avoidance of reaction 2. Bulky substituents on the equatorial and/or axial ligands may sterically hinder the coordination of a sixth ligand. Building a "superstructure" around the metal center is, in fact, a generalization of this idea. The use of equatorial ligands bearing a donor group on a pendant arm provides an alternative to the additional monodentate base.<sup>12</sup> This approach has been used extensively in porphyrin chemistry, but its application can be limited because of synthetic difficulties. A similar way to incorporate a fifth donor into a ligand is to use linear pentadentate ligands,<sup>9</sup> a variation that is easy for Schiff base ligands but not for porphyrins. It has long been known that cobalt(II) complexes with such ligands bind dioxygen in the absence of additional axial base.<sup>9</sup>

In our laboratories, we are studying the dynamics of dioxygen binding to cobalt(II) complexes which were designed to have vacant coordination sites. A recent publication,<sup>13</sup> reported our observations with lacunar macrobicyclic ligand complexes of cobalt(II). The lacunar structures of the ligands prevents the coordination of solvent or axial base at the sixth position while accommodating the small O<sub>2</sub> molecule. Oxygenation reactions for these complexes were found to be fast, with extremely low activation energies ( $\leq 2 \text{ kcal/mol}$ ). In the results reported in this paper, a different class of compounds has been used, namely, complexes with linear pentadentate ligands dissolved in noncoordinating solvents (for structures and ligand abbreviations see Figure 1). By choosing relatively simple compounds which are quite different from those studied previously,<sup>13</sup> we set out to determine whether or not low-barrier O<sub>2</sub> binding is a general property of pentacoordinate cobalt(II) complexes. This paper also compares the kinetics of O<sub>2</sub> binding to bridged lacunar complexes with the kinetics of dioxygen binding to closely related nonbridged derivatives.

## Experimental Section

The unbridged pentacoordinate cobalt(II) complexes Co(SalMeDPT) and Co(acacMeDPT) were synthesized according to refs 14 and 9, respectively.<sup>9,14</sup> The bridged complexes Co(p-XyacacMeDPT) and Co(C6acacMeDPT) were obtained by the method of Busch and co-workers.<sup>15</sup> The complexes (for structures and abbreviations see Figure 1) were characterized by IR, UV-vis, and mass spectroscopy, and their ability to bind dioxygen was demonstrated by ESR and UV-vis



**Figure 1.** Structural formulas and abbreviations for the cobalt(II) dioxygen carriers.

spectroscopy. The ESR spectra of frozen solutions of the oxygenated complex were characteristic of cobalt(II) dioxygen adducts, with parameters corresponding to those previously described.<sup>9,15a,d,16,17</sup> The changes in the UV-vis absorption spectra upon oxygenation were also in a good agreement with published data.<sup>9,14a,15a,d</sup> The acetone used for kinetic measurements was dried over molecular sieves (3 Å), distilled, and degassed. Drying of acetone over K<sub>2</sub>CO<sub>3</sub> should be avoided, because the resulting impurities influence the oxygenation reaction in unpredictable ways.

Fast atom bombardment (FAB) mass spectra were obtained using a VG ZAB MS mass spectrometer equipped with a Xenon gun. The matrix was either a mixture of 3:1 dithiothreitol-dithioerythriol (FAB/MB) or 3-nitrobenzyl alcohol (FAB/NBA).

Dioxygen affinities were determined by spectrophotometric titration with dioxygen. The titrations were carried out in a 1 cm gastight quartz cell with a bubbling tube. Spectra were recorded on a Varian 2300 spectrometer connected *via* an IEEE interface to an IBM PC which allowed for automatic instrument control and data collection. Dioxygen/

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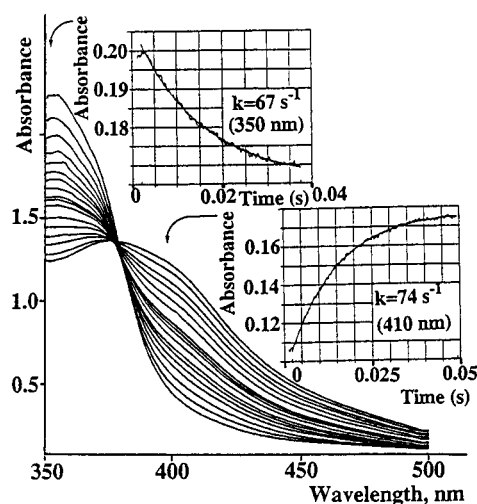
nitrogen gas mixtures were generated using Tylan FC-260 mass flow controllers. Dioxygen concentrations were maintained at a constant value during the dioxygen-binding measurements by bubbling gas, having the proper O<sub>2</sub> concentration, through the solution for 4 min at constant temperature prior to measurement. The cell holders were connected to a Neslab constant temperature circulation system, which gave temperature precision of  $\pm 0.3$  °C. The cell compartment was purged with dry nitrogen gas to prevent the condensation of moisture on the optical faces at low temperatures. Dioxygen binding equilibrium constants were determined from the UV-visible spectral changes as a function of dioxygen partial pressure<sup>18</sup> and were fitted, on an IBM Model 80 PS/2 computer, to the Ketelaar equation<sup>19</sup> using a BASIC program written in this research group.

Kinetic measurements were performed at low temperatures ( $-75$  to  $-40$  °C) using a Hi-Tech Scientific (Salisbury, Wiltshire, England) Canterbury CryoStopped-Flow instrument equipped with stainless steel plumbing and a stainless steel mixing cell, the latter having sapphire windows. The instrument was connected to an IBM computer with IS-2 Rapid Kinetic Software. The instrument's SHU-41 low-temperature flow unit was coupled to an MG-60 monochromator (supplied by Bentham Instruments Ltd., Reading, Berks, England, and described in their manual as a M-300 monochromator) and PM-60B photomultiplier using flexible light guides. The mixing chamber, as well as two stainless steel coils which delivered the cobalt(II) and dioxygen solutions, respectively, were immersed in a temperature-controlled bath filled with methanol. This bath was placed in a dewar filled with liquid nitrogen. The methanol bath was cooled by liquid nitrogen evaporation, and its temperature was monitored using a platinum resistance sensor and maintained to  $\pm 0.1$  K using a temperature-controlled thyristor power unit (both from Hi-Tech). The mixing time of the cell was 2 ms.

Reactions were run in acetone solution. Kinetic measurements were performed for different starting concentrations of the unbridged cobalt(II) complexes ( $7 \times 10^{-6}$ – $5 \times 10^{-5}$  M) and dioxygen ( $7 \times 10^{-6}$ – $5 \times 10^{-3}$  M). Measurements for the bridged complexes were limited to a narrow range of relatively low concentrations, because higher concentrations of the reagents caused the reactions to proceed too rapidly for measurement with this apparatus. The 2 mL Hamilton gastight driving syringes were placed in the anaerobic, nitrogen-purged unit. The dioxygen solutions of known concentration were prepared by bubbling the appropriate of N<sub>2</sub>/O<sub>2</sub> mixture through the solvent in a Hamilton gastight 10 mL syringe. The N<sub>2</sub>/O<sub>2</sub> gas mixtures were generated using Tylan FC-260 mass flow controllers. The solubility of O<sub>2</sub> in acetone at 25 °C (the temperature at which dioxygen solutions were prepared for our kinetic measurements) is reported to be 11.5<sup>20a</sup> or 11.0 mM.<sup>20b</sup> An average value of 11.2 mM was used in our calculations of O<sub>2</sub> concentration. The dioxygen concentration did not change upon cooling because the system was closed, and the solutions were not in contact with the gas phase (small variations in solvent density were not taken into account). The cobalt(II) complex solutions were prepared in a glovebox and placed in 10 mL, Hamilton gastight syringes equipped with 3-way valves. Whenever possible, pseudo-first-order conditions were used; they were achieved using an excess of dioxygen or, in some cases, an excess of complex. In these cases the kinetic curves were fit to a single exponential equation. In other cases, when neither reagent was used in large excess, a second-order fit was applicable. At each concentration, a series of 8–12 shots were run, and an average rate constant was calculated; standard deviations were within 10% of the magnitude of rate constants. Reproducibility of at least 20% was established by repeated preparation and mixing of starting solutions.

## Results

**Equilibrium Measurements.** The dioxygen affinities of the pentacoordinate cobalt(II) complexes, Co(SalMeDPT), Co(acacMeDPT), and Co(pXyacacMeDPT) (for structures and abbreviations see Figure 1), were measured by dioxygen titration

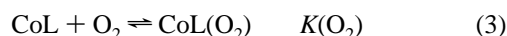


**Figure 2.** Absorbance changes during oxygenation of Co(SalMeDPT) ( $1 \times 10^{-4}$  M) in acetone at  $-39$  °C. Partial pressure of dioxygen: 0, 3.82, 7.63, 11.45, 15.27, 19.08, 22.90, 30.53, 38.17, 50.93, 76.40, 101.87, 152.8, 229.2, 382.0, 764.0 Torr. Inset: Kinetic traces at 350 and 410 nm superimposed with first-order (one-exponential) curve fits measured at  $-75$  °C; initial concentration of O<sub>2</sub> =  $1.12 \times 10^{-3}$  M, initial concentration of Co(SalMeDPT) =  $2.00 \times 10^{-5}$  M.

**Table 1.** Dioxygen Affinities of Cobalt(II) Pentadentate Schiff Base Complexes in Acetone Solutions Determined by a Dioxygen Titration Technique

<i>t</i> , °C	<i>K</i> (O <sub>2</sub> ), Torr <sup>-1</sup>	<i>K</i> (O <sub>2</sub> ), M <sup>-1</sup>
	Co(SalMeDPT)	
-39.0	0.024(1)	$1.63 \times 10^3$
-30.5	0.0060(3)	$4.05 \times 10^2$
-20.0	0.0025(1)	$1.68 \times 10^2$
	Co(acacMeDPT)	
-40.0	>5	> $3.4 \times 10^5$
	Co(pXyacacMeDPT)	
-32	0.715(7)	$4.85 \times 10^4$
-20	0.13(1)	$8.82 \times 10^3$
-10	0.072(2)	$4.89 \times 10^3$
0.00	0.0245(9)	$1.66 \times 10^3$
10	0.0085(3)	$5.77 \times 10^2$
20	0.0050(2)	$3.39 \times 10^2$

techniques described elsewhere.<sup>18</sup> The measurements were performed in acetone solutions at temperatures ranging from  $-40$  to  $+20$  °C. For all three compounds, absorbance changes corresponding to O<sub>2</sub> adduct formation were observed in the UV-vis spectra:<sup>9,14a,15a,d</sup>



In the case of Co(SalMeDPT), isosbestic behavior was observed at low temperatures (from  $-40$  to  $-20$  °C) (Figure 2), and the absorbance changes were found to be completely reversible. At higher temperatures, however, partial autoxidation of the complex was observed during the process of taking measurements. This is reflected in both the nonisosbestic spectral changes and in our failure to again observe the initial spectrum of the nonoxygenated complex after purging with N<sub>2</sub>. Consequently, the dioxygen affinity of this complex was determined over the  $-40$  to  $-20$  °C temperature range (Table 1). Enthalpy and entropy changes for the oxygenation reaction were determined from van't Hoff plots:  $\Delta H = -14$  kcal/mol,  $\Delta S = -45$  eu (standard state: 1 M<sup>21</sup>).

For the analogous acetylacetonate derivative, Co(acacMeDPT), oxygenation resulted in an absorbance increase in the 300–600 nm wavelength range. Even at  $-40$  °C, however, partial decomposition of the initially formed dioxygen adduct was observed within 10–20 min (absorbance decreased, and the

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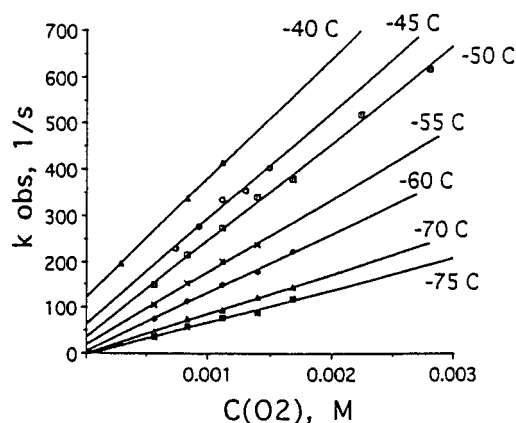
initial spectrum of the nonoxygenated cobalt(II) complex was not restored after saturation of the solution with pure  $N_2$ . Consequently, we were unable to determine the precise dioxygen affinity for this complex by our titration techniques. We were able to estimate that, at  $-40^\circ C$ ,  $P_{50}$  is less than 0.2 Torr and  $K(O_2) > 5 \text{ Torr}^{-1}$ . Additional evidence for the strong dioxygen affinity of  $Co(acacMeDPT)$  is provided in the kinetic measurements section of this paper.

It was shown earlier<sup>15a,d</sup> that bridged, pentadentate, Schiff base cobalt(II) complexes derived from acetylacetonate are fairly stable toward autoxidation, and some dioxygen binding equilibrium constants have been determined for them.<sup>15a,d</sup> In this work, the  $O_2$  affinity of  $Co(pXyacacMeDPT)$  in acetone solution was measured. Upon oxygenation, absorbance increases were observed in the spectral range from 300 to 600 nm, and these absorbance changes were completely reversible even at room temperature. The calculated values of  $K(O_2)$ , measured at different temperatures, are tabulated in Table 1. The following enthalpy and entropy changes due to dioxygen binding were calculated from the van't Hoff plot:  $\Delta H = -13 \text{ kcal/mol}$ ,  $\Delta S = -33 \text{ eu}$  (standard state:  $1 \text{ M}^{21}$ ).

**Kinetic Measurements.** The kinetics of dioxygen binding were measured by a spectrophotometric stopped-flow technique in the temperature range from  $-75$  to  $-40^\circ C$ . The cryogenic technique used here has several advantages over conventional methods: (1) At low temperature the reactions are slower and easier to measure. (2) The equilibrium of eq 1 is shifted toward dioxygen adduct formation which increases the observed changes in absorbance. (3) Autoxidation is retarded. The reactions studied in this paper are fast on the stopped-flow time scale, especially for the bridged complexes which have a typical reaction time of about 20 ms. For this reason, all readily controllable conditions were adjusted to slow down the reactions, for example by decreasing reagent concentrations or by decreasing the temperature. These measures improved the precision of the rate constant measurements significantly, and in some cases, the measurements were only possible under such extreme conditions.

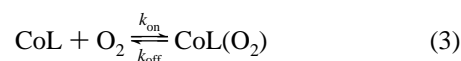
The absorbance changes at different wavelenghtes in the kinetic stopped-flow experiments correspond very well to the spectral changes observed in the conventional dioxygen titration experiments (Figure 2). For all compounds studied, only one process was observed on the stopped-flow time scale (up to 10 s). This shows that autoxidation reactions do not interfere with the dioxygen binding process under our experimental conditions. In most cases, a large (at least 10-fold) excess of dioxygen, with respect to the cobalt(II) complex, was used, and experimental data were fitted to a single exponential equation. Under pseudo-first-order conditions, the observed rate constants did not depend on the concentration of cobalt(II) complex and increased linearly with increases in dioxygen concentration.

For the simple reversible  $O_2$  binding reaction (eq 3), the observed rate constants depend on both the rate constant for binding and the rate constant for dissociation ( $k_{on}$  and  $k_{off}$ ). When



**Figure 3.** Graphs of observed rate constants versus dioxygen concentration during oxygenation of  $Co(SalMeDPT)$  in acetone measured at different temperatures. Initial concentration of cobalt complex in acetone =  $2.00 \times 10^{-5} \text{ M}$ .

a large excess of dioxygen is present in the reaction mixture, eq 5 holds.<sup>22</sup>



$$\frac{d[CoL]}{dt} = k_{obs}[CoL] \quad (4)$$

$$k_{obs} = k_{on}[O_2] + k_{off} \quad (5)$$

Linear plots of  $k_{obs}$  vs  $[O_2]$  were obtained for all three complexes for which the variation of dioxygen concentration was possible:  $Co(SalMeDPT)$ ,  $Co(acacMeDPT)$ , and  $Co(pXyacacMeDPT)$ ; e.g., Figure 3. Ideally, such plots allow one to determine the values of both rate constants,  $k_{on}$  and  $k_{off}$ , from the slope and intercept, respectively, of the straight line. In practice, however, the intercepts of these plots are sometimes close to 0 and, therefore, may fail to yield precise values for  $k_{off}$ . This happens when  $k_{on}[O_2] \gg k_{off}$  indicating that the oxygenated complex is the predominant species in the reaction mixture. It can be seen from Figure 3 that, for the  $Co(SalMeDPT)-O_2$  system, only the values of  $k_{on}$  could be determined at temperatures below  $-60^\circ C$ , while both kinetic parameters could be calculated at temperatures above  $-60^\circ C$ . For another unbridged complex,  $Co(acacMeDPT)$ , only  $k_{on}$  values were accessible, because the equilibrium (eq 3) was completely shifted to the right over the entire temperature range ( $-75$  to  $-40^\circ C$ ). This observation confirms the strong dioxygen affinity of  $Co(acacMeDPT)$ . For the bridged complexes, measurements were limited by fast reaction rates. In the case of the *p*-xylylene-bridged compound,  $Co(pXyacacMeDPT)$ , measurements were taken over the temperature range from  $-75$  to  $-50^\circ C$  and the binding rate constants were determined at several temperatures, but the dissociation rate constant could be determined only at  $-50^\circ C$ . For the fastest of the complexes,  $Co(C6acacMeDPT)$ , measurements were only possible at  $-70^\circ C$  and at low dioxygen concentrations ( $<0.1 \text{ mM}$ ), under second-order conditions; alternatively, pseudo-first-order conditions were applied in which the cobalt complex was in excess with respect to  $O_2$ . The absorbance changes measured in these kinetic experiments corresponded to complete formation of the 1:1 dioxygen adduct. This allowed us to disregard the  $O_2$  dissociation process (reverse reaction 3) in the treatment of the kinetic data. Representative kinetic data are summarized in Table 2.

(21) It should be noted that because different units ( $\text{Torr}^{-1}$  or  $\text{M}^{-1}$ ) are used to express the values of equilibrium constants in the literature, two different approaches have been used for the calculation of  $\Delta S$ . Here we used, equilibrium constant values in units of  $\text{M}^{-1}$  for the determination of entropy. In this case, the standard state of dioxygen is a hypothetical solution of  $O_2$  in acetone with an activity of 1. Alternatively, if the units for  $K$  are  $\text{Torr}^{-1}$ , the standard state of  $O_2$  is the gas phase with the partial pressure of  $O_2$  equal to 1 Torr. The latter approach has been used, for example, in a relevant publication.<sup>15a,d</sup> It has to be pointed out that one needs to know the solubility of  $O_2$  in order to calculate the dioxygen concentration in solutions; the precision and reliability of these numbers are usually relatively low, which limits the accuracy of  $K$  and  $\Delta S$  calculations by the former method.

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**Table 2.** Selected Rate Constants of Dioxygen Binding and Dissociation Processes

complex	-70 °C	-50 °C		-40 °C	
	$k_{\text{on}}, \text{M}^{-1} \text{s}^{-1}$	$k_{\text{on}}, \text{M}^{-1} \text{s}^{-1}$	$k_{\text{off}}, \text{s}^{-1}$	$k_{\text{on}}, \text{M}^{-1} \text{s}^{-1}$	$k_{\text{off}}, \text{s}^{-1}$
Co(SalMeDPT)	$8.84(7) \times 10^4$	$2.10(4) \times 10^5$	38(2)	$2.51(7) \times 10^5$	130(8)
Co(acacMeDPT)	$8.5(2) \times 10^5$	$1.0(1) \times 10^6$		$1.20(5) \times 10^6$	
Co(pXyacacMeDPT)	$3.96(8) \times 10^5$	$1.74(5) \times 10^6$	98(2)		
Co(C6acacMeDPT)	$5.0(7) \times 10^6$				

**Table 3.** Kinetic Parameters for O<sub>2</sub> Binding

compd	solvent/base	<i>t</i> , °C	binding			dissociation			ref
			$k_{\text{on}}, \text{M}^{-1} \text{s}^{-1}$	$\Delta H_{\text{on}}^{\ddagger}$ , kcal/mol	$\Delta S_{\text{on}}^{\ddagger}$ , eu <sup>a</sup>	$k_{\text{off}}, \text{s}^{-1}$	$\Delta H_{\text{off}}^{\ddagger}$ , kcal/mol	$\Delta S_{\text{off}}^{\ddagger}$ , eu <sup>a</sup>	
Co(SalMeDPT)	acetone	25	$1.4 \times 10^6$ <sup>c</sup>	3.0(3) <sup>d</sup>	-19	$1.0 \times 10^5$ <sup>c</sup>	15	14	this work
		0	$8.3 \times 10^5$ <sup>c</sup>			$1.2 \times 10^4$ <sup>c</sup>			
		-70	$8.8 \times 10^4$			3.3 <sup>c</sup>			
Co(acacMeDPT)	acetone	25	$2.1 \times 10^6$ <sup>c</sup>	1.2(4) <sup>d</sup>	-26				this work
		0	$1.7 \times 10^6$ <sup>c</sup>						
		-70	$8.5 \times 10^5$						
Co(pXyacacMeDPT)	acetone	25	$7 \times 10^7$ <sup>c</sup>	6.6(4) <sup>d</sup>	-3	$5.3 \times 10^5$ <sup>b</sup>			this work
		0	$3 \times 10^7$ <sup>c</sup>			$4.5 \times 10^4$ <sup>b</sup>			
		-70	$4 \times 10^5$						
Co(C6acacMeDPT)	acetone	-70	$5 \times 10^6$						this work
Co(Salen)	pyridine	0	$5.7 \times 10^5$			35.9 <sup>b</sup>			11a
Co(Sal(±)pn)	pyridine	0	$7.0 \times 10^3$			1.7 <sup>b</sup>			11b
Co(Sal(+ )bn)	pyridine	0	$3.2 \times 10^2$			0.13 <sup>b</sup>			11b
Co(Sal(m)bn)	pyridine	0	$7.6 \times 10^2$			0.24 <sup>b</sup>			11b
Co(Sal(-)chxn)	pyridine	0	$6.2 \times 10^3$			27.0 <sup>b</sup>			11b
Co(Sal(m)chxn)	pyridine	0	<10 <sup>2</sup>						11b
Co(C5Cyc)	acetone/1-methylimidazole	25	$2.0 \times 10^6$ <sup>c</sup>	0.7	-28	$1.1 \times 10^4$ <sup>c</sup>	18.4	22	13
Co(C6Cyc)	acetone/1-methylimidazole	25	$1 \times 10^8$ <sup>c</sup>	4	-10				13
CoMb(SW)	water	25	$4.0 \times 10^7$	9.2	7.6	$4 \times 10^3$	17.8	17.7	6b
FeMb(horse)	water	25	$1.4 \times 10^7$	5.5	-7.2	$1.0 \times 10^1$	19	9.4	6a

<sup>a</sup> Standard state: 1 M. <sup>b</sup> Calculated from equilibrium constant and  $k_{\text{on}}$ . <sup>c</sup> Extrapolation from a different temperature range. <sup>d</sup> Esd values are given in parentheses; the real accuracy of  $\Delta H^{\ddagger}$  values is lower and can be estimated as  $\pm 1$  kcal/mol.

The dioxygen binding rate constants measured at different temperatures were used to obtain activation parameters for all of the complexes except Co(C6acacMeDPT).<sup>22</sup> Activation parameters were also determined for the O<sub>2</sub> dissociation reaction in the case of Co(SalMeDPT) (Figure S1 (Supporting Information)). From the activation parameters rate constants were extrapolated to 25 °C for comparison with other oxygen carriers (Table 3).

To check the validity of our data, a comparison was made between the results of equilibrium measurements and those of the independent kinetic measurements. For reaction 3, a very simple relationship exist between the equilibrium and kinetic parameters:

$$K(\text{O}_2) = k_{\text{on}}/k_{\text{off}} \quad (6)$$

$$\Delta H = \Delta H_{\text{on}}^{\ddagger} - \Delta H_{\text{off}}^{\ddagger} \quad (7)$$

Because of instrument limitations, the dioxygen titration experiments (direct equilibrium measurements) and stopped-flow kinetic measurements were conducted over different temperature ranges, but these temperature ranges overlapped for Co(SalMeDPT). At -39 °C, the dioxygen affinity measured by dioxygen titration is  $K(\text{O}_2)_{\text{eq}} = 1.63 \times 10^3 \text{ M}^{-1}$  (Table 1); at -40 °C, kinetic measurements gave  $k_{\text{on}} = 2.51 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$ ,  $k_{\text{off}} = 129.5 \text{ s}^{-1}$  (Table 2), and  $K(\text{O}_2)_{\text{kin}} = k_{\text{on}}/k_{\text{off}} = 1.94 \times 10^3 \text{ M}^{-1}$ . This good agreement between  $K(\text{O}_2)_{\text{eq}}$  and  $K(\text{O}_2)_{\text{kin}}$  increases both the credibility of our kinetic data and the validity of eq 3. The enthalpy of oxygenation for Co(SalMeDPT) is also in agreement with activation parameters for the O<sub>2</sub> binding and dissociation processes: from dioxygen titration experiments,  $\Delta H_{\text{eq}} = -13$  kcal/mol; from kinetic measurements,  $\Delta H_{\text{on}}^{\ddagger} = 3$  kcal/mol,  $\Delta H_{\text{off}}^{\ddagger} = 15$  kcal/mol, and  $\Delta H_{\text{kin}} = 3 - 15 = -12$  kcal/mol.

Although, in the case of Co(pXyacacMeDPT), equilibrium and kinetic measurements were conducted at different temper-

atures, comparison is still possible by extrapolation of the dioxygen affinity to a lower temperature (-50 °C). This extrapolation gives  $K(\text{O}_2)_{\text{eq}} = 3.2 \times 10^5 \text{ M}^{-1}$ , while the value of  $K(\text{O}_2)_{\text{kin}} = 1.74 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}/14.0 \text{ s}^{-1} = 1.2 \times 10^5 \text{ M}^{-1}$  was calculated from the results of stopped-flow experiments. In this case, the agreement between equilibrium and kinetic data is not excellent, but it is acceptable. Obviously, the extrapolated  $K(\text{O}_2)_{\text{eq}}$  suffers a significant decrease in accuracy, and the accuracy of  $K(\text{O}_2)_{\text{kin}}$  is, in turn, relatively low because of the unfavorable ratio of the fast forward and slow reverse reaction rates.

In summary, the oxygenation of the cobalt(II) complexes with pentadentate Schiff base ligands studied in this paper occurs in accord with reaction 3. Equilibrium constants for dioxygen binding for two of the complexes were determined using a dioxygen titration technique. A direct cryogenic stopped-flow method was used to study the kinetics of oxygenation. The rate constants of dioxygen binding were determined for four compounds, while the rate constants of dioxygen dissociation were determined for only two. The results are summarized in Tables 2–4. The results obtained by dioxygen titration are in agreement with those determined using the stopped-flow method.

## Discussion

The four cobalt complexes with pentadentate Schiff base ligands studied in this paper (Figure 1) have been previously characterized as dioxygen carriers.<sup>9,14,15a,d,16,17</sup> Here, we were primarily interested with the kinetics of dioxygen binding to the vacant cobalt(II) coordination site. The need to maintain a vacant coordination site, as well as the low-temperature experimental conditions, limited our choice of solvents. Specifically, the solvent had to be noncoordinating, have a melting point lower than -75 °C, and remain reasonably nonviscous at low temperatures. The solvent of choice, acetone, meets these

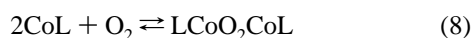
**Table 4.** Equilibrium Data for Dioxygen Binding with Cobalt(II) Schiff Base Complexes

compd	solvent/base	<i>t</i> , °C	stoichiometry of O <sub>2</sub> adduct	<i>K</i> (O <sub>2</sub> ), Torr <sup>-1</sup> (for 2:1 adducts, Torr <sup>-1</sup> M <sup>-1</sup> )	<i>P</i> <sub>50</sub> , Torr	Δ <i>H</i> <sup>o</sup> , kcal/mol	Δ <i>S</i> <sup>o</sup> , eu <sup>a</sup>	ref
Co(Salen)	bis(2-methoxyethyl) ether/4-Me-pyridine	25	2:1	8.12	12	-10.3	-30	26a
Co(Salen)	pyridine	0	1:1	8 × 10 <sup>-2</sup>	12.5			11a
Co(Salen)	DMSO	20	1:1	3.1 × 10 <sup>-3</sup>	323	-16	-67	24
Co(Salen)	pyridine	20	1:1 (?)	8.9 × 10 <sup>-2</sup>	11.2	-12.4	-47	23a
Co(acacen)	pyridine	20	1:1 (?)	0.36	2.75	-15.1	-53	23b
Co(acacen)	toluene/pyridine	0	1:1	8.32 × 10 <sup>-3</sup>	120.2	-17.3	-72.7	8
Co(SalMeDPT)	DMSO	20	1:1 (?)	6.77 × 10 <sup>-3</sup>	148			25
Co(SalMeDPT)	CH <sub>2</sub> Cl <sub>2</sub>	-12	1:1	1.54 × 10 <sup>-3</sup>	649	-9.8	-50.3	14a
		20		1.9 × 10 <sup>-4 b</sup>	5.3 × 10 <sup>3 b</sup>			
Co(SalMeDPT)	acetone	0	1:1	2.9 × 10 <sup>-4 b</sup>	3.5 × 10 <sup>3 b</sup>	-14	-68	this work
		25		3.3 × 10 <sup>-5 b</sup>	3.0 × 10 <sup>4 b</sup>			
Co(acacMeDPT)	acetone	-40	1:1	>5	<0.2			this work
Co(pXyacacMeDPT)	acetone	0	1:1	2.45 × 10 <sup>-2</sup>	40.8	-13.0	-56	this work
		20		5.0 × 10 <sup>-3</sup>	200			
Co(pXyacacMeDPT)	toluene	25	1:1	1.4 × 10 <sup>-3</sup>	714	-13.2	-57	15a,d
		0		9.6 × 10 <sup>-3</sup>	104			
Co(C6acacMeDPT)	toluene	25	1:1	0.15	6.67	-16	-58	15a,d
		0		1.66	0.60			
Co(BHBETPY)	bis(2-methoxyethyl) ether	0	2:1	10.7	9.6	-12.0	-39	26b
Co(MBA)	bis(2-methoxyethyl) ether	0	1:1	1.58 × 10 <sup>-4</sup>	6 × 10 <sup>3</sup>			26b
Co(MHBA)	bis(2-methoxyethyl) ether	0	1:1	2.23 × 10 <sup>-3</sup>	4.5 × 10 <sup>2</sup>			26b

<sup>a</sup> Standard state: 1 Torr. <sup>b</sup> Extrapolated from the temperature dependence of oxygen affinity measured at different temperatures.

criteria. Because the dioxygen affinities of our complexes in acetone are not available in the literature, and dioxygen affinities are known to be solvent-dependent,<sup>2</sup> the dioxygen affinities of three cobalt(II) complexes in acetone were determined in this work. The results are summarized in Table 1. Some equilibrium data on oxygenation of our complexes or similar compounds in different solvents have been published.<sup>2,8,11,14a,15a,d,23-26</sup>

The dioxygen affinities of cobalt(II) oxygen carriers derived from salicylaldehyde are usually relatively low, due to the relatively poor electron-donating properties of the ligands.<sup>24</sup> An unusually high dioxygen affinity (2 orders of magnitude higher than determined in this investigation) has been reported for Co(SalMeDPT) in DMSO solution<sup>25</sup> (Table 4). On the other hand, when the same complex was studied in toluene or methylene chloride,<sup>14a</sup> the values for dioxygen affinity were found to be quite close to those reported here for acetone solutions (Table 4). Both here and in ref 14a, *K*(O<sub>2</sub>) was measured at relatively low temperatures (from -40 to -12 °C) by means of spectrophotometric dioxygen titrations. In both cases, isosbestic behavior was observed, suggesting that no autoxidation occurs under experimental conditions. In contrast, measurements in ref 25 were conducted at room temperature using electrochemical techniques.<sup>25</sup> Our results suggest that more than one chemical reaction occurs in parallel in the Co(SalMeDPT)/O<sub>2</sub> system at room temperature. According to our kinetic data, the formation of a 1:1 dioxygen adduct is fast for this system (Figure 1); the dioxygen uptake reported in ref 25 is slow, requiring about 0.5 h for completion. The dioxygen uptake observed in ref 25 seems, however, to be reversible; the original voltammogram of the cobalt(II) complex could be restored by purging the oxygenated solution with nitrogen gas. Most likely, those authors<sup>25</sup> studied 2:1 dioxygen adduct formation (eq 8),



while we studied 1:1 complex formation (eq 3). Additional

evidence for this interpretation is Martell's observation that high temperatures favor 2:1 dioxygen adduct formation (*μ*-peroxy dimers), while low temperatures favor 1:1 dioxygen adduct formation,<sup>26</sup> which can be explained by different thermal parameters for 1:1 and 2:1 adduct formation.<sup>27</sup> The dioxygen affinities of several other pentacoordinate cobalt(II) Schiff base complexes derived from salicylaldehyde are available in ref 26. The *P*<sub>50</sub> for the two compounds which form 1:1 adducts are close to the numbers obtained in this paper and in ref 14a for Co(SalMeDPT). The *P*<sub>50</sub>'s for the compound which forms a 2:1 adduct are close to the numbers obtained in ref 25 for, presumably, the 2:1 adduct of Co(SalMeDPT) with O<sub>2</sub> (Table 4).

As expected, on the basis of the greater electron donor strength of the ligands, the dioxygen affinities of the acetylacetonone derivatives are higher than those of the analogous salicylaldehyde-derived compounds. In our case, an estimate of *K*(O<sub>2</sub>) for Co(acacMeDPT) (Table 1) shows that the dioxygen affinity of Co(acacMeDPT) is at least 2 orders of magnitude higher than that for Co(SalMeDPT). To the best of our knowledge, no precise *K*(O<sub>2</sub>) values for cobalt(II) complexes with acetylacetonone-derived pentadentate Schiff base ligands have been determined (the relatively fast autoxidation of such complexes might be a reason for this). A comparison of the tetradentate Schiff base complexes, Co(acacen) and Co(Salen), suggests that the dioxygen affinity of the former might be some 4 times greater than that of the latter.<sup>23</sup> This is the same trend we observe for our pentadentate complexes, but the difference between the salicylaldehyde derivatives and the acetylacetonone derivatives is significantly greater in our case. Although 1:1 dioxygen adduct formation was postulated in ref 23, as well as in several other publications dealing with Co(Salen) oxygenation,<sup>11,24</sup> it was later shown, by direct volumetric measurements of dioxygen uptake, that Co(Salen) forms a 2:1 complex with O<sub>2</sub>.<sup>26</sup> It is difficult to tell whether the results of early *K*(O<sub>2</sub>) measurements on Co(Salen) complexes should be explained on the basis of 1:1 adduct formation or on the basis of 2:1 adduct formation.

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For cobalt(II) complexes with bridged lacunar pentadentate Schiff base ligands, accurate measurements of dioxygen affinities in toluene solutions have been reported.<sup>15a,d</sup> We have extended measurements to acetone solutions for the *p*-xylylene-bridged compound, Co(pXYacacMeDPT). Qualitatively, the behavior of the complex was the same in acetone as it was in toluene; quantitatively, however, a small difference in equilibrium constants was observed (Tables 1 and 4). It is difficult, on the basis of the limited data available, to analyze the effect of solvent on the energetics of dioxygen binding to Co(pXYacacMeDPT). It is clear, however, that any differences which arise from using acetone instead of toluene are small and that the extensive data obtained earlier<sup>15a,d</sup> for the oxygenation of bridged, pentadentate cobalt(II) Schiff base complexes in toluene solutions can be extended to describe the behavior of the same complexes in acetone.

The main focus of this research was to study the dynamics of dioxygen binding to a vacant coordination site on selected cobalt(II) complexes. For the majority of previously studied cobalt(II) dioxygen carriers, all six coordination sites of the cobalt(II) ion were occupied either by ligand donor atoms or by solvent molecules. The dissociation of one of the coordinated groups was a requirement for O<sub>2</sub> binding. The process of ligand/solvent dissociation could be a slow, rate-determining step for the oxygenation reaction or a relatively fast pre-equilibrium process. In any event, either the enthalpy change or the activation enthalpy of sixth ligand dissociation would contribute to the activation energy for dioxygen binding. Not surprisingly, in the few cases where activation parameters have been determined for the oxygenation of Co(II) complexes,<sup>3,4,28</sup> relatively high values of activation energy (4–20 kcal/mol) were found. For the same systems, activation entropies were found to be positive and thus indicative of a dissociative process.<sup>3,4,28</sup> The activation volumes<sup>5c</sup> for dioxygen binding to two cobalt(II) macrocyclic complexes, Co(cyclam) and Co(hexamethylcyclam), were found to be close to 0 (the same is true for myoglobin<sup>29</sup>). This was explained in terms of a transition state in which Co–O<sub>2</sub> bond formation and Co–H<sub>2</sub>O bond dissociation occur to approximately the same extent.<sup>5c</sup>

The lacunar cyclidene cobalt(II) complexes, in which the sixth coordination site is vacant by design, provided a sharp contrast to the observations detailed immediately above. The rates of dioxygen binding were found to be fast with very small activation enthalpies (*ca.* 1–2 kcal/mol).<sup>13</sup> This result indicates that no significant bond alteration is necessary in proceeding to the transition state for Co–O<sub>2</sub> bond formation and that Co–O<sub>2</sub> bond formation is similar to radical combination processes.<sup>5,13</sup> In order to determine whether this striking feature of dioxygen binding dynamics is unique to cobalt(II) cyclidenes, or a more general property of cobalt(II) complexes having a vacant coordination site, we have studied and are reporting here on another family of pentacoordinate cobalt(II) dioxygen carriers.

It was found, in this study, that the activation energy for dioxygen binding to cobalt(II) complexes with unbridged pentadentate Schiff base ligands in acetone solutions is also very small (1.2 kcal/mol for CoacacMeDPT and 3 kcal/mol for CoSalMeDPT). Negative activation entropies were also found for the oxygenation reactions (Table 3), and these are characteristic of associative processes, providing further evidence that Co–O<sub>2</sub> bond formation, rather than Co–solvent bond dissociation, occurs in the transition state. These results show that more

than one class of pentacoordinate cobalt(II) dioxygen carriers can undergo low activation barrier oxygenation. This observation provides new insight into the design of fast and efficient dioxygen carriers.

It should be noted that unusually small activation energies for dioxygen binding (about 1–3 kcal/mol) have also been found for some copper(I) complexes<sup>30a</sup> and for sterically hindered iron(II) porphyrins.<sup>31</sup> These interesting results were reported without comment. Our experience suggests that, in the case of the copper(I) compounds, vacant coordination sites were present (measurements were reported for the noncoordinating solvent CH<sub>2</sub>Cl<sub>2</sub>; a similar group of copper(I) complexes studied in propionitrile gave significantly higher  $\Delta H^\ddagger$  values<sup>30b</sup>). With respect to the sterically hindered picket fence porphyrins, the “fence” around the porphyrin<sup>31</sup> could play the same role as the bridge in cyclidenes,<sup>2a,13</sup> protecting the vacant site on iron(II) from coordination of a sixth ligand. The fast ( $k \approx 10^8 \text{ M}^{-1} \text{ s}^{-1}$ ), diffusion-controlled oxygenation of some sterically hindered cobalt(II) porphyrins fixed on a polymer membrane<sup>32</sup> also suggests very small activation enthalpies for these reactions. Consequently, the concept of a vacant coordination site appears to be generally applicable in predicting oxygenation barriers for transition metal complexes.

Although a vacant coordination site is an important premise for low-barrier oxygenation, other structural factors may account for an increase in the activation energy for dioxygen binding. For example, among the cobalt(II) complexes studied in this paper, the *p*-xylylene-bridged compound displayed the highest barrier for dioxygen binding (6.6 kcal/mol). It should be noted that the dioxygen affinity of Co(pXYacacMeDPT) is substantially smaller than the dioxygen affinities of other bridged complexes in the same family.<sup>15a,d</sup> This was explained in terms of steric control over dioxygen binding, because X-ray studies show a highly restricted cavity compared to that of the C<sub>6</sub> bridged compound.<sup>15d</sup> It is possible, therefore, that significant ligand rearrangement, which would result in a relatively high activation barrier for the oxygenation reaction, is required for dioxygen binding to Co(pXYacacMeDPT). On the other hand, a comparison of X-ray structures for the unbridged complex, Co(SalMeDPT), and its dioxygen adduct<sup>33</sup> reveals only minor structural changes upon oxygenation. This corresponds to a relatively low activation energy for dioxygen binding (Table 3).

A comparison of dioxygen affinities and rates of dioxygen binding for Co(SalMeDPT) and Co(acacMeDPT) (Tables 1–3) shows that the substantially higher O<sub>2</sub> affinity of the acetylacetonone derivative cannot be explained in terms of different O<sub>2</sub> binding rates. This means that the difference in dioxygen affinity between the two complexes is determined primarily by the difference in O<sub>2</sub> dissociation rates (eq 6). This finding is in agreement with the more general observation concerning dioxygen carriers that electronic factors influence the rate of dioxygen dissociation rather than the rate of dioxygen binding.<sup>3a,12</sup> A comparison of the kinetic data obtained here for Co(SalMeDPT) with the published kinetic data for Co(Salen) and its derivatives<sup>11</sup> reveals that the complex with a pentadentate ligand reacts significantly faster than the complexes with tetradentate ligands and separate axial bases. One possible

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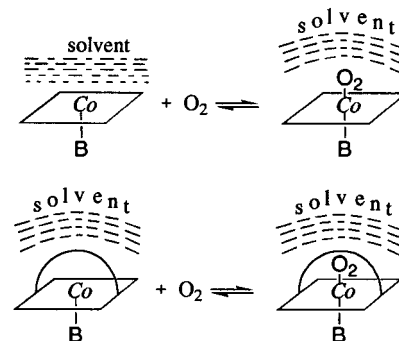
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reason for such behavior is the coordination of axial base as a sixth ligand (eq 2). If a second molecule of axial base is, in fact, coordinated, the dissociation of one axial ligand is a requirement for dioxygen binding. This would account for a relatively slow process. It should be noted, however, that the kinetic data<sup>11</sup> were obtained by electrochemical measurements. When using electrochemical techniques, it is difficult both to distinguish between 1:1 and 2:1 dioxygen adduct formation (see discussion above) and to interpret the results in terms of one distinct rate-determining step.

Our results indicate that the oxygenation of unbridged pentacoordinate cobalt(II) complexes is a low-barrier reaction with activation energies falling in the range 1–3 kcal/mol. The process is relatively fast, with second-order rate constants higher than  $10^6 \text{ M}^{-1} \text{ s}^{-1}$ . This is significantly faster than the oxygenation of relevant cobalt(II) complexes with Salen-like ligands. Even these high rates, however, are 2 orders of magnitude slower than the oxygenation rates of natural dioxygen carriers. Apparently, activation enthalpies cannot account for such a difference, and it must be concluded that relatively unfavorable activation entropies are responsible for the slower oxygenation rates of our unbridged complexes.

The situation changes dramatically when the vacant coordination site on cobalt(II) is protected with a bridge. Indeed, even the slowest of the bridged acetylacetonate derivatives, Co(pXyacacMeDPT), reacts with  $\text{O}_2$  approximately as fast as do myoglobin, hemoglobin, and coboglobin at room temperature (Table 3). Another bridged complex, Co(C6acacMeDPT), reacts approximately 1 order of magnitude faster than Co(pXyacacMeDPT) at low temperatures (the temperature dependence for the C6 bridged complex was not obtained, because the reaction rate exceeded instrument limitations at temperatures higher than  $-70 \text{ }^\circ\text{C}$ ). Apparently, the higher dioxygen affinity of Co(C6acacMeDPT), compared to Co(pXyacacMeDPT), can be attributed to a faster rate of dioxygen binding. Similar steric retardation of dioxygen binding has been reported previously for sterically hindered porphyrin complexes<sup>3a,12</sup> and for lacunar cyclidene complexes.<sup>13</sup>

It is difficult to explain why the bridged acac derivatives bind dioxygen faster than the closely similar unbridged parent complex Co(acacMeDPT). For porphyrin oxygen carriers, the addition of superstructure to the porphyrin platform led, in some cases, to increased dioxygen affinity and increased rates of dioxygen binding,<sup>31,34</sup> while in other cases the opposite trend was observed.<sup>35,36</sup> Several explanations have been suggested for the former effect, among them the following: (1) The coordinated  $\text{O}_2$  molecule can form hydrogen bonds with some groups (*e.g.* amides) in the superstructure.<sup>35,37</sup> (2) Unmodified porphyrin platforms are “shielded” with solvent, and the solvent structure has to be rearranged significantly upon oxygenation; this unfavorable process is not necessary for the oxygenation of superstructured compounds (Figure 4).<sup>31</sup> (3) The “ortho” effect is present in which phenyl groups with ortho substituents destabilize the domed form of the metalloporphyrin, thus facilitating small ligand binding.<sup>38</sup> In our case, there is no



**Figure 4.** Nonspecific “solvent shielding” of the coordination site in unbridged cobalt(II) complexes, as compared to the “bridge shielding” in the corresponding lacunar complexes (suggested by Collman and co-workers<sup>31</sup>).

obvious site for hydrogen bonding between a coordinated  $\text{O}_2$  molecule and the bridge. The second explanation could, however, be viable. This suggests that the role of solvent in the oxygenation of cobalt(II) complexes is not limited to the specific solvation of the cobalt ion. Nonspecific solvation of the whole molecule may also influence the dynamics of dioxygen binding to Co(II) complexes. Remarkably, this is not a small effect as the data in Table 3 reveal. Another possible explanation for the observed rate data (somewhat related to the ortho effect in porphyrin chemistry) is changes in ligand conformation due to bridging. The tetragonal pyramidal coordination geometry found in Co(II) complexes with bridged ligands Co(C6acacMeDPT) and Co(pXyacacMeDPT)<sup>15d</sup> is favorable for dioxygen adduct formation, while, in the case of unbridged Co(acacMeDPT), a more significant ligand rearrangement may possibly be needed. The absence of structural information for this unbridged complex limits conclusions. It should be emphasized that these suggested explanations for the different oxygenation rates of bridged *vs* unbridged complexes remain speculative. Further investigations are required to fully understand the role of ligand superstructure, and its interplay with solvents, on the processes of dioxygen binding.

## Conclusions

Dioxygen binding to cobalt(II) complexes with pentadentate Schiff base ligands in acetone solution is a fast process with a low activation enthalpy and negative activation entropy. This reactivity with  $\text{O}_2$  is characteristic of cobalt(II) complexes having vacant coordination sites. The dioxygen affinity of the acetylacetonate Schiff base derivative is higher than the dioxygen affinity of the corresponding salicylaldehyde derivative, largely because of different  $\text{O}_2$  dissociation rates. The oxygenation rates of the lacunar complexes were found to be higher than the oxygenation rates of the parent unbridged complex and approximately equal to the oxygenation rates of natural oxygen carriers. Nonspecific solvation of the coordination site in the unbridged species may be responsible for retarded reaction at the unprotected vacant site.

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**Supporting Information Available:** A plot of the temperature dependence of the rate constants for Co(SalMeDPT) (1 page). Ordering information is given on any current masthead page.

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