Cation Radicals of Phenothiazines. Part 2.[1] Electron Transfer between Aquacobalt(III) and *N*-Alkylphenothiazines

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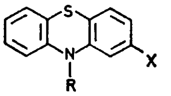
The kinetics of electron transfer between aquacobalt(III) and some *N*-alkylphenothiazines has been investigated by means of the stopped-flow technique. The reaction consists of a one-electron transfer with formation of the corresponding cation radicals. The reaction rates have been found to be independent of acidity in the range $0.40 \leqslant [HClO_4] \leqslant 2.00$ mol dm^{-3}, suggesting that Co^{3+}(aq) is the main reacting species. The results are discussed in terms of the Marcus cross-reaction equation for outer-sphere electron-transfer reactions.

STUDIES of the oxidation kinetics of series of related organic compounds have played an important role in understanding the mechanism of electron-transfer reactions involving metal-ion complexes. The benzenediols, which have been used in previous investigations, allowed us to assess a dependence of activation energy on free-energy change for reactions with different complexes {$[IrCl_6]^{2-}$ and related complexes,[2] $[FeL_3]^{3+}$ where L = phenanthroline- or bipyridine-like ligands,[3] $[Mo(CN)_8]^{3-}$,[4] and $[Fe(CN)_6]^{3-}$ (ref. 4)} and to estimate their characteristic intrinsic parameters. Different behaviour has been observed with aquametal ions, like manganese(III) [5] or cobalt(III).[6] These reactions were found to be largely acid-dependent: the reaction path which pertains to M^{3+} exhibited a relationship between the free energy of activation and free-energy change, while the rates of the paths referred to $[M(OH)]^{2+}$ species were found to be almost independent of the nature of the organic substrate.

TABLE 1

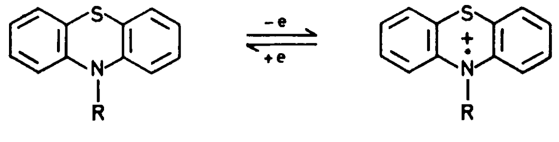
Reduction potentials of investigated phenothiazines and spectral characteristics of the corresponding cation radicals



Compound	X	R	$E^\ominus$/V *	λ/nm	$10^{-3}\varepsilon$/dm^3 mol^{-1} cm^{-1}
(1)	OH	$CH_2CH_2CH_2NMe_2$	0.62_5	562	9.5
(2)	H		0.72	514	9.4
(3)	OMe	$CH_2CH_2CH_2NMe_2$	0.71	566	9.0
(4)	H	$CH_2CH_2CH_2NMe_2$	0.71_5	513	9.2
(5)	Cl	$CH_2CH_2CH_2NMe_2$	0.78	525	10.2
(6)	H	$CH_2CH_2NEt_2$	0.82	511	10.5
(7)	H	$CH_2CH(Me)NMe_2$	0.86_5	515	9.3
(8)	H	$CH(Me)CH_2NMe_2$	0.89	524	8.8

* At 25.0 °C, $[HClO_4] = 1.00$ mol dm^{-3}, and $I = 1.0$ mol dm^{-3}.

The present paper deals with the kinetics and mechanism of electron transfer between Co^{III} in aqueous perchlorate solutions and a series of *N*-alkylphenothiazines. This class of compounds, which are of pharmaceutical interest,[7] has been found to be particularly versatile in these investigations: they give rise to a one-electron oxidation, with formation of the corresponding cation radicals,[7] according to:



ptz ptz$^{\bullet+}$

The cation radicals of phenothiazines are stable in acidic solution, are strongly absorbing in the visible,[7] and the reduction potentials and self-exchange rates between radicals and parent molecules are known.[1]

EXPERIMENTAL

Reagents.—Cobalt(III) solutions were prepared by anodic oxidation of cobalt(II) perchlorate solutions, as previously described.[6] The investigated phenothiazines (collected in Table 1) were supplied by Rhône-Poulenc. Perchloric acid and sodium perchlorate (E. Merck) were used to adjust the acidity and the ionic strength. Doubly distilled water was used.

Procedure.—The kinetic runs were performed with a Durrum–Gibson stopped-flow spectrophotometer, the phenothiazines being present in excess. The concentrations of organic substrates were varied from 5×10^{-5} to 2×10^{-4} mol dm^{-3} and the acidity range investigated was 0.40—2.00 mol dm^{-3} $HClO_4$. The spectral range 520—560 nm

TABLE 2

Kinetic parameters for oxidation of phenothiazines with Co^{III} [a]

Compound	k [b]/$dm^3\ mol^{-1}\ s^{-1}$ 7.5 °C	k [b]/$dm^3\ mol^{-1}\ s^{-1}$ 25.0 °C	$\Delta H^\ddagger$ [b] / kcal mol^{-1}	$\Delta S^\ddagger$ [c] / cal K^{-1} mol^{-1}
(1)	$(5.8 \pm 0.4) \times 10^4$	$(1.8 \pm 0.2) \times 10^5$	10.2	0
(2)	$(2.1 \pm 0.2) \times 10^4$	$(7.5 \pm 0.6) \times 10^4$	11.6	2
(3)	$(1.5 \pm 0.1) \times 10^4$	$(6.0 \pm 0.5) \times 10^4$	12.6	6
(4)	$(2.3 \pm 0.2) \times 10^4$	$(9.2 \pm 0.9) \times 10^4$	12.6	6
(5)	$(1.3 \pm 0.1) \times 10^4$	$(4.0 \pm 0.3) \times 10^4$	10.1	−3
(6)	$(4.8 \pm 0.5) \times 10^3$	$(1.9 \pm 0.2) \times 10^4$	12.5	3
(7)	$(4.3 \pm 0.3) \times 10^3$	$(1.4 \pm 0.1) \times 10^4$	10.7	−4
(8)	$(4.2 \pm 0.4) \times 10^3$	$(1.3 \pm 0.1) \times 10^4$	10.2	−6

[a] $[Co^{III}]_0 = 1.5 \times 10^{-5}$—$2.0 \times 10^{-5}$ mol dm^{-3}, $I = 2.0$ mol dm^{-3} ($Na[ClO_4]$). [b] The error is 1.2—1.5 kcal mol^{-1}. [c] The error is 4—5 cal K^{-1} mol^{-1}.

was found particularly useful owing to the high absorptivity of the cation radicals (see Table 1). Second-order plots were linear for at least three half-lives. Alternatively, as suggested by Corbett,[8] a reaction with only two-fold excess of one reagent can be treated as a pseudo-first-order reaction, with an error in the calculated k of $<2\%$ for 60% conversion. The agreement between the data computed with the two methods was good.

RESULTS AND DISCUSSION

Stoicheiometry.—By operating with Co^{III} as the limiting reagent in order to avoid further oxidation of cation radicals,[7] and by evaluating spectrophotometrically the cation radical formed, a stoicheiometric ratio of 1 : 1 was established, according to reaction (1).

$$Co^{III} + ptz \longrightarrow Co^{II} + ptz^{\cdot +} \qquad (1)$$

Kinetics.—The second-order plots were found to be linear and the first-order dependence on the concentration of each reagent corresponds to the rate law (2).

$$-d[Co^{III}]/dt = k[Co^{III}][ptz] \qquad (2)$$

No effect of acidity was observed in the range 0.40—2.00 mol dm^{-3} $HClO_4$. The second-order rate constants, averaged from the data obtained at different acidities, are collected in Table 2 together with corresponding activation parameters.

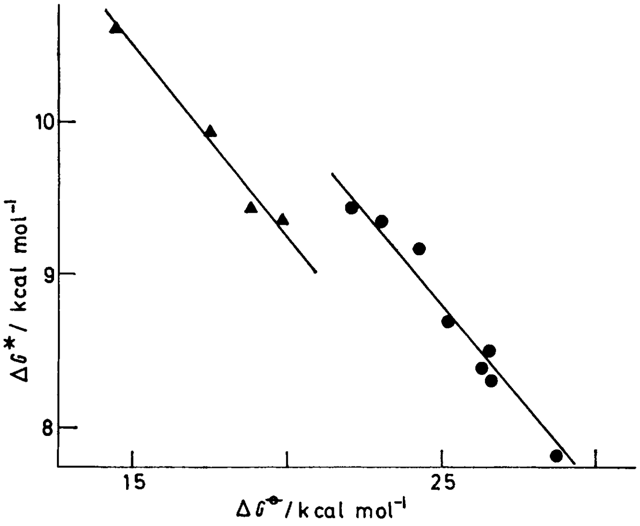
The absence of an acid-dependent path is rather unusual in oxidation reactions involving Co^{III}, particularly with organic substrates.[9] The same behaviour, *i.e.* a negligible contribution of the hydrolysed form to the reaction progress, has been observed also in the oxidation with Fe^{III} of the same phenothiazines.[1] In other outer-sphere electron transfers involving metal-ion complexes, an unfavourable reactivity ratio of the hydrolysed species compared with the unhydrolysed one has been observed.[10] Thus, in this case, the hydroxo-group is unable to act as bridging group which catalyses the electron-transfer act.

The values of k reported exceed the rate of water exchange in the co-ordination sphere of $Co^{3+}(aq)$,[9] thus suggesting an outer-sphere mechanism. Then, according to the Marcus theory,[11] a dependence of activation energy on free-energy change is expected, of the form (3)

$$\Delta G^*_{12} = \lambda_{12}[1 + (\Delta G^\ominus/\lambda_{12})]^2/4 \qquad (3)$$

(owing to the high ionic strength, the work terms have been neglected), where λ_{12} is the intrinsic parameter related to the self-exchange activation parameters through the relationship $\lambda_{12} = 2(\Delta G^*_{11} + \Delta G^*_{22})$ and ΔG^*_{12} may be obtained from the expression $k = Z\exp(-\Delta G^*_{12}/RT)$ where Z is the collision frequency assumed to be 10^{11} dm^3 mol^{-1} s^{-1}. Accordingly to equation (3), a plot of ΔG^*_{12} as a function of $\Delta G^\ominus$, for a small range of $\Delta G^\ominus$ with respect to λ_{12}, is practically linear with slope $\frac{1}{2}[1 + (\Delta G^\ominus/2\lambda_{12})]$. By computing λ_{12} from the reported values of self-exchange activation energy for $ptz^{\cdot +}$–ptz ($\Delta G^*_{11} = 3.3$ kcal mol^{-1}) [1] and for Co^{III}–Co^{II} ($\Delta G^*_{22} = 13.8$ kcal mol^{-1}),[9] the slope is expected to have a value 0.31 : the Figure shows that the experimental data agree with this expectation (slope 0.28).†

As is usual in cobalt(III) oxidations,[6,9] for the present systems the calculated rate constants differ from the experimental ones by about five orders of magnitude. Several explanations have been advanced in order to account for this discrepancy.[9,12]



Variation of ΔG^* with $\Delta G^\ominus$ for outer-sphere oxidation of Co^{III}: (●) phenothiazines; (▲) phenanthroline complexes of Fe^{II}. The reduction potential of Co^{III}–Co^{II} has been assumed as 1.87 V (ref. 9)

It is also interesting to compare the present results with the oxidation of $[FeL_3]^{2+}$ systems [13] and in the Figure the data concerning such systems are included for comparison: the observed slopes are very similar and

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† Throughout this paper: 1 cal = 4.184 J.

the slight difference in the intercepts can be attributed to small differences in the intrinsic terms of the two families.[14] This suggests that the same mechanism, that is a simple outer-sphere electron transfer, is operating in the oxidation with Co^{III} of phenanthroline complexes of iron(II) and of phenothiazines.

[8/1351 *Received, 20th July*, 1978]

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