Reduction by Polymetallic Complex Hydrides. Part 1. Dihydrobis-(pyrazol-1-yl)borates of Transition Metals with Cyclohexanone and Cyclohex-3-enone [1]

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The reactivity of Co^{II}, Ni^{II}, Cd^{II}, Cu^{II}, and Zn^{II} dihydrobis(pyrazol-1-yl)borates have been tested towards the ketonic function of cyclohexanone and cyclohex-3-enone under various experimental conditions. Reduction rate and selectivity vary with the nature of the transition metal, independently of both the molar ratio of hydride to ketone and the temperature.

In recent years the selective reducing ability of metal hydride complexes has been widely studied.[2] We have investigated the change in the reactivity of metal hydrides due to the introduction of a second metal (M') bonded to the original metal hydride through a π-electronic bridge, *i.e.* a ligand bonding to both M and M', containing suitable groups, which can vary the electron density of the M–H bonds.

Transition-metal poly(pyrazol-1-yl)borates (1), described by Trofimenko,[3-5] exhibit these ideal structural features. We have synthesized the complex hydrides $[M'(H_2BPz_2)_2]$ (Pz = pyrazol-1-yl; M' = CO^{II}, Ni^{II}, Cd^{II}, Cu^{II}, or Zn^{II}) whose structures are known,[6,7] and studied their reactivity towards cyclohexanone and cyclohex-3-enone, as models for steroids which will be investigated later.

RESULTS AND DISCUSSION

The reduction processes were carried out under a variety of experimental conditions, in order to gain information on the effects of temperature, solvent nature,

The reduction of cyclohexanone has been performed in a number of aprotic solvents (n-hexane, tetrahydrofuran, chloroform, and benzene) in which the complexes were soluble. However all the data at different temperatures and varying molar ratios (Table 1) refer to reactions in benzene, in which a better reproducibility was achieved. Data relating to reductions with Cu and Zn derivatives are not reported because of very low reactivity (<16% of reduction product at 50 °C in the presence of an excess of hydride).

In all cases the reaction rate increases on increasing the temperature and hydride concentration, the main difference in reactivity being due to the nature of the transition metal.

The different electronic configurations of the metal ions along the series (Co^{2+} $3d^7$; Ni^{2+} $3d^8$; Cu^{2+} $3d^9$; Zn^{2+} $3d^{10}$; Cd^{2+} $4d^{10}$) and the different geometries of the resulting complex hydrides [6,7] (square-planar for Ni and Cu derivatives; tetrahedral for Co, Cd, and Zn derivatives) make it difficult to establish the relation between the reactivity of the various complex hydrides and the nature of the transition metal in the absence of mechanistic studies. Experimental results indicate that the reactivity increases along the series Ni ≫ Co > Cd > Cu ≥ Zn, a sequence which does not correspond with either the 'electronegativity' of the metals or the stability constants of their aza-chelate complexes.[8]

TABLE 1

Reduction reactions of cyclohexanone with $[M(H_2BPz_2)_2]$

| Complex hydride | Conditions [a] | | | |
	Temperature (°C)	Time/ min	Molar ratio [b] [ketone] : [hydride]	Cyclohexanol [c] yield (%)
$[Ni(H_2BPz_2)_2]$	25	190	2 : 1	91.1
	25	60	1 : 1	100.0
	25	10	1 : 2	94.2
	50	30	2 : 1	90.2
	50	15	1 : 1	98.0
$[Co(H_2BPz_2)_2]$	25	200	2 : 1	81.8
	25	60	1 : 1	95.1
	25	10	1 : 2	93.1
	50	30	2 : 1	85.4
	50	15	1 : 1	86.3
$[Cd(H_2BPz_2)_2]$	25	225	2 : 1	60.7
	25	60	1 : 1	50.2
	25	10	1 : 2	48.8
	50	30	2 : 1	63.2
	50	15	1 : 1	64.4

[a] [ketone] = 0.05 M in benzene. [b] Reactions at 1 : 2 molar ratio at 50 °C are not reported because they are too fast to be correctly measured. [c] The reaction mixtures contain only cyclohexanol and cyclohexanone detectable by g.l.c. analysis.

and molar ratio ([ketone] : [hydride]), both on the reaction rate and selectivity.

M = B

M'= Co, Ni, Cu, Zn, Cd

(1)
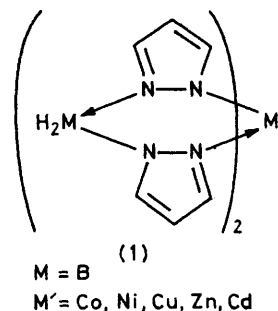
Since the Cu and Zn derivatives do not readily reduce ketonic or aldehydic † groups, the possibility of their use in the reduction of more reactive carbonyl groups to

† In experiments with benzaldehyde, at room temperature in benzene, with Cu and Zn derivatives in the molar ratio 2 : 1 (aldehyde : hydride) the yield of benzyl alcohol, after 3 h, is <6%.

obtain aldehydes could be interesting. The reaction of benzoyl chloride at room temperature with [Cu-(H$_2$BPz$_2$)$_2$] leads to benzaldehyde in low yield (25—35%) and to the acylation product of the ligand (1-benzoyl-pyrazole) in good yield (65—75%). The very poor yield of benzoyl benzoate (5—8%) confirms that very little reduction of the aldehyde group occurs. Using [Zn(H$_2$BPz$_2$)$_2$] under the same reaction conditions, benzaldehyde in *ca.* 10% yield and more 1-benzoyl-pyrazole than in the former case was obtained.

We are currently studying reduction of acyl halides with Zn and Cu derivatives containing hindering groups in the pyrazole ring, which prevent side-reactions involving the nitrogen atoms of the ring.

In early studies [9] on metallic hydrides, the observation was made that although carbon–carbon double bonds are generally not reduced with either sodium borohydride or lithium aluminohydride, frequent exceptions to the rule were observed in the reduction of αβ-unsaturated aldehydes and ketones, which often results in a mixture

Since cyclohex-3-enol does not react at room temperature with the metal dihydrobis(pyrazol-1-yl)borates used, the formation of cyclohexanol could be due to a conjugate reduction, by transfer of a hydride ion to the β-carbon atom, as reported in the reactions of both lithium aluminohydride and sodium borohydride with αβ-unsaturated ketones.[10c]

In conclusion, a good selectivity towards the carbonyl group is achieved only with Ni and Cd derivatives. These results parallel previous findings [10a] on the reduction of cyclopent-3-enone with a number of metal hydrides, mainly lithium hydridodimethoxyaluminate (cyclopent-3-enol 91%; cyclopentanol 9%). However, in the present case the experimental conditions used (aprotic solvents, 20—50 °C) are much less limiting than in that one (THF, 0 °C).

An extensive study of the chemical and stereochemical reactivities of these and other polymetallic hydrides is now under investigation in order to verify, and, if possible, to generalize these results.

TABLE 2

Reduction reactions of cyclohex-3-enone with [M(H$_2$BPz)$_2$]

Complex hydride	Conditions [a]			Products (%)				Percentage reduction
	Temperature (°C)	Time/h	Molar ratio [ketone] : [hydride]	Cyclohexanone	Cyclohexanol	Cyclohex-3-enone	Cyclohex-3-enol	
[Ni(H$_2$BPz$_2$)$_2$]	25	72	1 : 1	<1%	4.7 (5.6)	21.5	73.8 (94)	78.5
	25	48	1 : 2	<1%	4.9 (5.4)	9.8	85.3 (94.6)	90.2
	50	15	1 : 1	<1%	11.7)12.4)	7.7	80.6 (87.3)	92.3
	50	8	1 : 2	<1%	10.3 (10.6)	4.5	85 (89)	95.5
[Co(H$_2$BPz$_2$)$_2$]	25	72	1 : 1	<1%	17.0 (30.1)	41.9	39.7 (67.1)	58.1
	25	48	1 : 2	1.9 (3.4)	24.1 (43)	43.9	30.0 (53.6)	56.1
	50	15	1 : 1	3.6 (5.7)	33.8 (53.9)	37.3	25.3 (40.8)	62.7
	50	8	1 : 2	3.6 (4.0)	46.0 (51.0)	9.9	40.5 (45.0)	90.1
[Cd(H$_2$BPz$_2$)$_2$]	25	72	1 : 1	<1%	1.5 (8.2)	81.9	16.5 (91.5)	18.1
	25	48	1 : 2	<1%	1.9 (5.7)	66.8	30.9 (93.1)	33.2
	50	15	1 : 1	<1%	2.8 (7.0)	59.8	36.6 (91.1)	40.2
	50	8	1 : 2	1.8 (4.3)	2.9 (6.9)	58.2	37.1 (88.8)	41.8

[a] [ketone] = 0.05 M in benzene. [b] The percentages relative to the converted original substrate are in parentheses.

of products. Methods for selective reduction to allylic alcohols have been described.[9–13]

We have studied the reduction of cyclohex-3-enone with various transition metal dihydrobis(pyrazol-1-yl)-borates; data for the reactions of the Ni, Co, and Cd derivatives in benzene at 20 and 50 °C, and in various molar ratios, are reported in Table 2. In this case also the low reactivity of Cu and Zn derivatives is confirmed (reduction products <8% at 50 °C, in the presence of an excess of hydride).

The reduction rate of the unsaturated substrate is, as found for derivatives of sodium borohydride,[14] in every case lower than that of the saturated one. The results indicate that the relative amount of reduction products depends on the nature of the transition metal, and is independent of the [ketone] : [hydride] molar ratio.

A lower selectivity at 50 than at 20 °C is always observed, but differences due to the transition metal are maintained; with Ni, Co, and Cd derivatives at 50 °C cyclohexa-1,3-diene (5—18% yield) is also obtained.

EXPERIMENTAL

Materials.—Commercial pyrazole (Fluka) was recrystallized from diethyl ether–n-hexane (3 : 1, v/v). Cyclohexanone, cyclohex-3-enone, cyclohexanol, cyclohex-3-enol, and cyclohexa-1,3-diene (Fluka), were purified by distillation under reduced pressure. Potassium borohydride (Fluka) and solvents were used without further purification. Benzene saturated with water was used, in order to obtain free alcohols directly from reaction mixtures.

Physical Measurements.—The yields of the reactions were measured with a Hewlett–Packard 5830 A gas chromatograph under the following conditions: Carbowax 20M 5% on Chromosorb G sil. column, 9 ft × 0.125-in o.d.; temperature 180 °C; flow of helium 22 ml min^{-1}; calculation mode, internal standard (n-tetradecane).

Preparation of Dihydrobis(pyrazol-1-yl)borates of Co[II], Ni[II], Cu[II], Cd[II], *and* Zn[II].—The complex hydrides were prepared as reported in the literature [3–5] and purified either by chromatography through Florisil (B.D.H., 80—100 mesh; eluant CHCl$_3$) or by crystallization from n-heptane or toluene.

Typical Reduction Reactions of Cyclohexanone and Cyclohex-3-enone.—To the solution of ketone (1 mmol) in benzene (20 ml), the metal dihydrobis(pyrazol-1-yl)borates dissolved in the same solvent were added in varying molar ratios. The resulting solution was maintained at constant temperature with stirring on a thermostatted bath, and the yields of the reaction products measured at fixed times by gas chromatography. The same result was obtained either by direct analysis of the reaction mixture, or by quenching the mixture with dilute mineral acid, separation of the organic layer, drying with anhydrous sodium sulphate, and measuring free alcohols or the derived acetates.

Reduction of Benzoyl Chloride by the Dihydrobis(pyrazol-1-yl)borates of Cu^{II} *and* Zn^{II}.—To the solution of benzoyl chloride (1 mmol) in benzene (20 ml) an equimolar solution of the metal complex hydride in the same solvent was slowly added at room temperature with stirring, and the reaction course followed by t.l.c. [Silica gel Merck GF$_{254}$; eluant, cyclohexane–ethyl acetate (85 : 15, v/v)]. After 1 h the reaction was stopped by the addition of dilute hydrochloric acid to the mixture cooled in an ice bath. The organic layer was then separated, dried with anhydrous sodium sulphate, and the amounts of benzaldehyde and benzoyl benzoate formed determined by gas chromatography. From an unquenched aliquot, 1-benzoylpyrazole was separated by chromatography on a silica gel column [cyclohexane–ethyl acetate (85 : 15, v/v)].

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