Facile dichloromethane activation and phosphine methylation. Isolation of unprecedented zwitterionic organozinc and organocobalt intermediates[†]

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Both C–Cl bonds of CH₂Cl₂ are readily activated by CoCl₂ and metallic Zn allowing quantitative methylation of phosphines; unprecedented zwitterionic Co(II) and Zn(II) intermediates have been characterized which display α -metallated phosphoniums.

The activation of the relatively inert C-Cl bond of chloroalkanes represents a considerable challenge of chemical and environmental relevance.¹ It would be particularly desirable to use the carbon moiety of a chloroalkane for alkylation chemistry. Activating both C-Cl bonds of a gem-dichloroalkane represents an additional difficulty and whereas CH2Br2, CH2I2 or CH2CII are used in e.g. Simmons-Smith cyclopropanation,² the cheaper CH₂Cl₂ is far less exploited,³ because of its much lower reactivity. Thus, the recently reported activation of the C-Cl bonds of CH₂Cl₂ in the presence of pyridine and Ni(0) nanoparticles required 100 °C and 10 h reaction time.⁴ As part of our studies on the coordination chemistry of P,O- and P,N-functional phosphines,⁵ we were interested in isolating Co(1) complexes, inter alia because of their possible involvement in the cobalt-catalyzed homogeneous carbonylation of methanol,⁶ and unexpectedly discovered that CH₂Cl₂ can be used as a methylation reagent under mild reaction conditions.

In an attempt to synthesize Co(1) complexes bearing the phosphinooxazoline $Ph_2PCH_2C=NCH_2CH_2O(1_{ox})$ or its thio analog $Ph_2PCH_2C=NCH_2CH_2S(1_{th})$ (Scheme 1), which have



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† Electronic supplementary information (ESI) available: Supplementary X-ray structures, crystallographic details, VT NMR spectra, experimental procedures and spectroscopic data. CCDC 697021–697024, 697025 ($5\cdot1/2C_6H_{14}$), 697026 (2_{ox}), 697027 (2_{th}), 697028 (4), 697029 (4-ZnCl₂) and 697030. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b817728g

‡ Current address: Key Laboratory of Engineering Plastics and Beijing National Laboratory for Molecular Science, Institute of Chemistry, Chinese Academy of Sciences, Beijing, 100190, China. a rich chemistry,⁷ anhydrous CoCl₂ was reacted with these ligands and Zn powder in CH₂Cl₂, in a 1 : 1 : 1 molar ratio. Unexpectedly, complexes 2_{ox} and 2_{th} , respectively, were isolated (Scheme 1), in which the zinc ion is coordinated by three chlorides and an N-bound Ph₂P⁺(Me)CH₂C=NCH₂CH₂O cation (Fig. 1).§ Phosphorus methylation has resulted in a phosphonium cation associated with a negatively charged ZnCl₃ group in a zwitterionic complex.

Although related chemistry has been observed with cobalt, it required the use of highly sensitive Co(0) tetraphosphine complexes, produced *in situ* by reduction of Co(II) with Mg, and afforded a maximum theoretical yield of 50% based on phosphine.⁸ Our results prompted us to attempt to (i) generalize this reaction to other phosphines and (ii) establish the origin of the methyl group, CH₂Cl₂ being the obvious suspect. Phosphines P(*n*-Bu)₃, PMePh₂, PMe₂Ph and PPh₃ underwent methylation under the conditions used for 2_{ox} and 2_{th} and quantitative formation of cobalt metal was observed, according to [eqn (1)]:

$$2CH_2Cl_2 + 2PR_3 + 2CoCl_2 + 4Zn + 2H_2O$$

 $\rightarrow (R_3PMe)_2(ZnCl_4) + Zn(OH)_2 + 2ZnCl_2 + 2Co (1)$

When the reaction was performed in CD_2Cl_2 , the phosphonium cations $Ph_3P^+CD_3$ and $Ph_3P^+CD_2H$ were obtained after hydrolysis with D_2O or H_2O , respectively, confirming that CH_2Cl_2 is the methylating agent.

With MeCN as co-solvent, an intermediate of [eqn (1)] could be crystallized, $[Zn(\mu-Cl)Cl(CH_2PPh_3)]_2$ (4), in which each



Fig. 1 ORTEP plot of the X-ray structure of 2_{ox} . Ellipsoids at 50% probability level. Aromatic and oxazoline H atoms not shown for clarity. Selected bond distances (Å): Zn1–N1 2.051(2), Zn1–Cl3 2.2409(8), Zn1–Cl1 2.2562(8), Zn1–Cl2 2.2614(8), N1–C2 1.270(3), P1–C5 1.786(3).



Fig. 2 ORTEP plot of the X-ray structure of 4 (top) and structural diagram of the X-ray structure of $4 \cdot \text{ZnCl}_2$ (bottom). For $4 \cdot \text{ZnCl}_2$, the asymmetric unit is delimited by dashed lines, the polymer repeating unit by black lines. Ellipsoids at 50% level. Selected distances for 4 (Å): Zn1–Cl 2.025(2), Zn1–Cl1 2.3505(6), Zn1–Cl2 2.2491(7), C1–Pl 1.752(2). Similar values are found in $4 \cdot \text{ZnCl}_2$,†

metal centre is σ bound to the CH₂ carbon of a Ph₃P⁺CH₂group and coordinated by three chlorides, two of them bridging the tetrahedrally coordinated metal centres. Under anhydrous conditions, **4** is the only P-containing species detected after reaction and is isolated in high yields. In pure CH₂Cl₂, nonsolvated ZnCl₂ forms with **4** the unprecedented coordination polymer [**4**·ZnCl₂]_n (Fig. 2 and ESI†).§ In the di-zwitterionic complex **4**, the positive and negative charges are on the phosphorus and the Zn₂Cl₄ core, respectively. Similarly, **4**·ZnCl₂ is a poly-zwitterion. To the best of our knowledge, only two structures related to **4** have been reported for zinc.⁹

Addition of HCl or water to a solution of 4 readily afforded the phosphonium salts $(Ph_3PCH_3)_2(Zn_2Cl_6)$ and $(Ph_3PCH_3)_2$ (ZnCl₄), respectively (crystal structures in ESI[†]). Similar chemistry was observed for PMePh₂, PMe₂Ph and P(n-Bu)₃. Although the presence of Co(II) prevents NMR monitoring of the reaction of [eqn (1)], we suggest that complexes $[CoCl_2(PR_3)_2]$ are formed first and consistently, $[CoCl_2(PPh_3)_2]$ reacted with Zn and CH₂Cl₂ to form 4 and, upon hydrolysis, $Ph_{3}P^{+}CH_{3}$. After reduction of [CoCl₂(PPh₃)₂] to [CoCl(PPh₃)₃],¹⁰ oxidative-addition of CH₂Cl₂ could afford the transient species [Co^{III}Cl₂(CH₂Cl)(PR₃)₃], by analogy to related Rh(1) systems (Scheme 2).11 Similarly, oxidative-addition of aromatic C-Cl bonds to Co(1) results in octahedral Co(11) complexes.¹² Coupling between the ligands PR₃ and -CH₂Cl would then afford the metallated $-CH_2P^+R_3$ group, as observed with rhodium.¹³ An intermolecular coupling is less likely since when the PR₃: Co ratio was reduced to one, no appreciable change in reactivity was observed. Finally, reduction and transmetallation from Co to Zn would yield 4 (Scheme 2, path A) and restore the Co(II) reagent, which is in turn reduced by Zn to the active species [CoCl(PPh₃)₃]. This cyclic reaction may be viewed



Scheme 2 Suggested pathways for CH₂Cl₂ activation and phosphine alkylation.

as catalytic in cobalt. A PR₃: Co ratio higher than 3 was found detrimental for a complete conversion.

In a separate experiment (Scheme 2, path B), a solution of $[CoCl(PPh_3)_3]$ in CH_2Cl_2 became blue within a few minutes under nitrogen, indicating oxidation to Co(II). The highly reactive, zwitterionic complex $[CoCl_2(CH_2PPh_3)PPh_3]$ (5)§ was crystallized from the mother liquor. Its metal centre is tetrahedrally coordinated by PPh₃, CH_2PPh_3 and two chlorides (Fig. 3). $[CoCl_2(PPh_3)_2]$ and PPh₃ are by-products of this reaction. The Co(II) intermediate (Scheme 2) is reduced by the Co(I) complex (comproportionation), rather than by Zn metal, which is absent in path B.



Fig. 3 ORTEP plot of the X-ray structure of 5 in $5 \cdot 1/2C_6H_{14}$. Ellipsoids at 50% level. Selected distances (Å): Co1–C1 2.040(6), Co1–Cl1 2.227(2), Co1–Cl2 2.235(2), Co1–P2, 2.407(2), C1–P1 1.738(7).

The reaction between $[CoCl(PPh_3)_3]$ and CH_2Cl_2 (Scheme 2, path B) can thus be written as follows:

$$2[CoCl(PPh_3)_3] + CH_2Cl_2$$

$$\rightarrow [CoCl_2(CH_2PPh_3)(PPh_3)]$$

$$+ [CoCl_2(PPh_3)_2] + 2 PPh_3 \qquad (2)$$

Since neither ZnCl₂ nor Zn are present in [eqn (2)], hypothetical Zn carbenoids, often invoked in the activation of dihalomethanes,¹⁴ are not involved here, although a carbene intermediate has been suggested in the reaction of Cr(II) complexes with CH₂Cl₂.¹⁵ In the CH₂Cl₂-based methylation of ketones with a Mg-TiCl₄-based system,¹⁶ no intermediate has been isolated. Our cobalt-based system thus involves steps closer to those suggested with the noble metals Rh(I), Ru(II) or Os(II),^{13,17} which, however, only led to stoichiometric reactions.¹⁸ In our case, Zn restores the active Co(I) species and allows the quantitative methylation of all the phosphines present. Formation of P-C bonds assisted by cobalt complexes has been reported from the attack of dibromo- or di-iodomethane on dinuclear phosphides.¹⁹ Whereas oxidativeaddition of organic chlorides to Co(1) complexes has been reported,¹² only one chloro, chloromethyl complex has been characterized from the photoassisted, oxidative-addition of CH₂Cl₂ to Co(1).²⁰ Although the chemistry of [CoCl(PPh₃)₃] has been intensively explored,²¹ it is surprising that, to the best of our knowledge, its fast reaction with CH₂Cl₂ has never been discussed.

We have shown here that CH_2Cl_2 can be readily activated by a cheap metal, without the need for an external Cl-abstracting reagent, and exploited for phosphorus methylation. The reaction involves easily accessible reagents and allows methylation of PPh₃ by CH_2Cl_2 , $CoCl_2$ and Zn to be carried out under air, in contrast to reactions involving Co(0) precursors.⁸ The phosphonium salts produced are well-known precursors to *e.g.* the very important class of phosphorus ylids. Our reaction appears general for aromatic and aliphatic phosphines, since variation of their stereo-electronic properties did not result in appreciable differences in reactivity. We have thus shown that challenging transformations considered limited to noble metals can be observed or even improved using a much cheaper metal such as cobalt.

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Notes and references

§ X-Ray diffraction data (173 K): 2_{0x} : C₁₇H₁₉Cl₃NOPZn, M = 456.02, $P2_1/c$, a = 12.8862(3), b = 8.4311(2), c = 18.2833(6) Å, $\beta = 98.131(1)$, V = 2439.7(2) Å³, Z = 4, $D_c = 1.540$ g cm⁻³, μ (MoKα) = 1.742 mm⁻¹, F(000) = 928, $R_{int} = 0.043$, R_1 ($I > 2\sigma(I)$) = 0.040, w R_2 ($I > 2\sigma(I)$) = 0.084 (218 param., 3158 obsd refl. 4749 unique); 4: C₃₈H₃₄Cl₄P₂Zn₂, M = 825.13, C2/c, a = 14.5489(7), b = 13.7296(3), 18.8997(8) Å, $\beta = 104.530(2)$, V = 3654.5(2) Å³, Z = 4, $D_c = 1.500$ g cm⁻³, μ (MoKα) = 1.720 mm⁻¹, F(000) = 1680, $R_{int} = 0.035$, R_1 ($I > 2\sigma(I)$) = 0.035, wR_2 ($I > 2\sigma(I)$) = 0.089 (208 param., 3964 obsd refl., 5318 unique); 4-ZnCl₂: C₇₆H₆₈Cl₁₂P₄Zn₆, M = 1922.80, $P\overline{1}$, a = 10.261(2), b =20.439(3), c = 21.995(3) Å, $\alpha = 63.454(3)$, $\beta = 86.058(9)$, $\gamma =$ 83.865(8), V = 4102(1) Å³, Z = 2, $D_c = 1.557$ g cm⁻³, μ (MoKα) = 1.362 mm⁻¹, F(000) = 5537, $R_{int} = 0.060$ R_1 ($I > 2\sigma(I)$) = 0.075, wR₂(*I* > 2σ(*I*)) = 0.206 (939 param., 20 257 obsd refl., 14 092 unique). **5**·1/2C₆H₁₄: C₃₇H₃₂Cl₂CoP₂·1/2C₆H₁₄, *M* = 668.45 (without solvent, see ESI[†]), *C2/c*, *a* = 24.424(1), *b* = 12.4340(9), *c* = 22.853(1) Å, *β* = 90.800(4), *V* = 6939.5(7) Å³, *Z* = 8, *D_c* = 1.279 g cm⁻³, μ(MoKα) = 0.769 mm⁻¹, *F*(000) = 2760, *R_{int}* = 0.060, *R*₁ (*I* > 2σ(*I*)) = 0.075, w*R*₂ (*I* > 2σ(*I*)) = 0.206 (379 param., 10 466 obsd refl., 6128 unique).

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