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Gold complexes derived from diphenyl-2-styrylphosphine †

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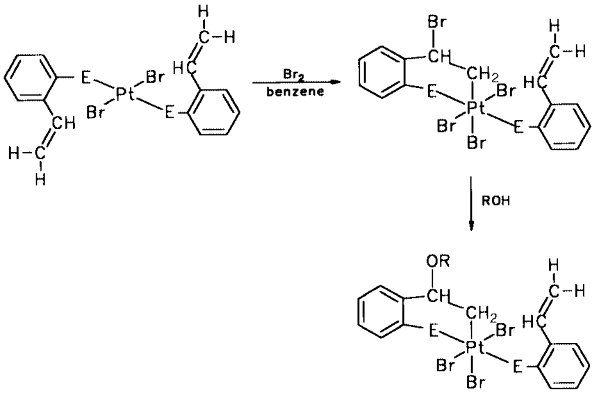
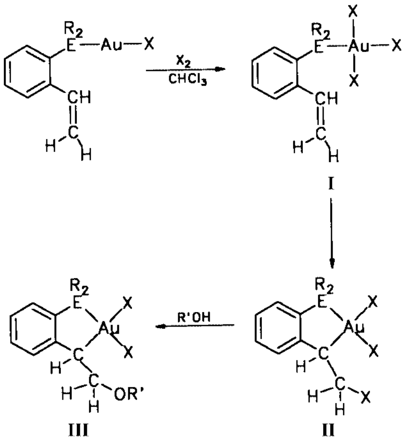
Complexes of diphenyl-2-styrylphosphine (sp) with gold, first reported in 1971, have been reinvestigated. [AuX(sp)] can be oxidised with X_2 for X = Cl or Br but not for X = I. The initial product, [AuX_3(sp)], undergoes a reversible rearrangement in which an Au–X bond adds across the styryl double bond to give [AuX_2(sp-X)] (sp-X = 2-CH-(CH_2X)$C_6H_4PPh_2$). The carbon-bound halide can be replaced by methoxy by reaction with methanol. [AuX_2(sp-Y)] (X = Cl or Br; Y = Cl, Br or OMe) react with iodide to give eventual reduction to [AuI(sp)], confirming that non-chelated [AuX_2(Y)(sp)] is unstable when X = I. Reduction reactions of this type complicate attempts to study halide-substitution reactions of [AuX_2(sp-Y)], but a variety of substituted products have been identified (*e.g.* those in which X = OAc CN, SCN, $\frac{1}{2}SCH_2CH_2NH_2$ or $\frac{1}{2}S_2CNEt_2$). Monosubstitution has been achieved with PPh_2R (R = Me or Ph). The crystal structure of [Au($SCH_2CH_2NH_2$)(sp-OMe)]PF_6 has been determined; in it and all other substituted products the softer, incoming ligand is *trans* to phosphorus.

More than thirty years ago the Nyholm group was investigating the dibromine-oxidation of metal complexes containing phosphine or arsine ligands which had olefinic substituents. Platinum(II) complexes of ligands containing *o*-styryl- or *o*-allyl-phenyl groups gave products which contained a new metal–bromine bond, a carbon–halogen bond and, quite unexpectedly, a metal–carbon bond (Scheme 1).[1] The organic halogen could readily be substituted by alkoxy groups, and the presence of the six-membered organo-platinum ring was demonstrated by X-ray crystallography.[2] This work was extended to gold, where the oxidised product was shown to contain a five-membered ring (**II**, Scheme 2).[3] Bennett has continued this work and has given (1986) a summary of otherwise unpublished data.[4] He mentions evidence for oxidation at the metal as a preliminary step to the formation of the gold–carbon bond, and for the reversible interconversion of the two gold(III) complexes. As far as we are aware, there have been no further publications on this system, but Professor Bennett has kindly supplied some additional information.[5]



Scheme 1 Reactions of platinum(II) styryl-ligand complexes (E = $AsMe_2$).[1]



Scheme 2 Reactions of gold(I) styryl-ligand complexes (ER_2 = PEt_2, PPh_2 or $AsMe_2$; R′ = H, Me or Et).[2]

These materials were of interest to us both because of the (still) highly unusual reversible addition of a gold–halogen bond across an organic double bond and because of their analogy to the C,N-chelated gold(III) complexes which we have found to show anti-tumour activity.[6,7] We have now attempted to extend the reactions of the *o*-styryldiphenylphosphine-gold(I) complexes using dichlorine and diiodine as oxidants; only the former was successful, and the diiodogold(III) complexes prepared by another route are susceptible to spontaneous reductive elimination. Intermediate gold(III) complexes are observed which confirm Bennett's proposed mechanism[4] for the formation of the cyclic complexes.

We have also examined the substitution chemistry of the organo-gold(III) compounds with a range of neutral and anionic ligands; these reactions are significantly different from those of the more familiar C,N-gold(III) systems.[6,8–14]

We have reported preliminary pharmacological data for two of the original compounds, and shown that limited solubility restricts their biological activity.[15]

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† Supplementary data available: analytical and NMR data, and time-dependence data for the reaction [AuX_2(sp-OMe)] (X = Br, Cl) with iodide, available from BLDSC (SUPP. NO. 57707, 7 pp.). See Instructions for Authors, Issue 1 (http://www.rsc.org/dalton).

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Experimental

Elemental analyses were carried out by the UMIST Chemistry Department Microanalytical Service (these data are deposited as supplementary material). IR spectra (4000–300 cm^{-1}) were recorded on a Nicolet 5PC Fourier transform infrared spectrometer in Nujol mulls between KBr plates, ^{1}H and ^{13}C NMR spectra on a Bruker AC-300 spectrometer at 200 and 50.3 MHz respectively in $CDCl_3$ or $(CD_3)_2SO$ at 25 °C using TMS as internal standard (these data are deposited in the supplementary material). $^{31}P\{^{1}H\}$ NMR spectra were obtained on a Bruker AC-200 spectrometer; chemical shifts are recorded relative to 85% aqueous H_3PO_4.

Preparations

Diphenyl-2-styrylphosphine was obtained by conventional Grignard synthesis from 2-bromostyrene and chlorodiphenylphosphine in THF. Recrystallisation was either from methanol or from pentane. Yield: 85%. mp 98 °C (lit. 97.7 °C).[16]

Chloro(diphenyl-2-styrylphosphine)gold(I). Sodium tetrachloroaurate dihydrate (1.0 g, 2.5 mmol) in water (25 cm^3) was reduced by addition to an excess of thiodiglycol (0.92 g, 7.5 mmol) in water (6.5 cm^3). A solution of diphenyl-2-styrylphosphine (0.72 g, 2.5 mmol) in chloroform (38 cm^3) was added dropwise over ten minutes and the mixture stirred for 3 hours. The chloroform layer was separated, and the remaining aqueous layer extracted with chloroform (3 × 20 cm^3). The chloroform extracts were combined, dried ($MgSO_4$), filtered and evaporated to dryness. The white residue was recrystallised from chloroform–ethanol. Yield: 88%. mp 175 °C (lit.[12] 173 °C).

Bromo-, iodo-, cyano-, and diethyldithiocarbamato-(diphenyl-2-styrylphosphine)gold(I) were obtained by conventional metathesis with lithium bromide/iodide, sodium diethyldithiocarbamate or silver cyanide in acetone.

Dibromo{2-bromo-1-[2-(diphenylphosphino)phenyl]ethyl}-gold(III), [AuBr$_2$(sp-Br)]. The complex [AuBr(sp)] (sp = diphenyl-2-styrylphosphine) (3.60 g, 6.38 mmol) in dichloromethane (67 cm^3) was treated at 25 °C with dibromine (1.02 g, 6.38 mmol) in dichloromethane (40 cm^3). The reaction mixture was stirred at 30 °C, for 4 hours. Removal of the solvent under reduced pressure gave the crude product as an orange solid, which was recrystallised from chloroform–diethyl ether. Yield: 3.93 g, 85%. [AuCl$_2$(sp-Cl)] was prepared similarly, using a saturated solution of dichlorine in dichloromethane as oxidant. Yield: 80%.

Dibromo{1-[2-(diphenylphosphino)phenyl]-2-methoxyethyl}-gold(III), [AuBr$_2$(sp-OMe)]. The complex [AuBr$_2$(sp-Br)] (0.10 g, 0.14 mmol) was refluxed in anhydrous methanol (50 cm^3) for 3 hours, giving a clear colourless solution. The solvent was removed and the residual off-white solid recrystallised from chloroform–methanol. Yield: 74 mg, 80%. [AuCl$_2$(sp-OMe)] and [AuCl$_2$(sp-OEt)] were prepared similarly, except that refluxing was continued for 3–4 d.

Diacetato{1-[2-(diphenylphosphino)phenyl]-2-methoxyethyl}-gold(III), [Au(OAc)$_2$(sp-OMe)]. The complex [AuBr$_2$(sp-Br)] (0.10 g, 0.14 mmol) was stirred with a suspension of silver acetate (96 mg, 0.56 mmol) in acetone (8 cm^3) for 2 h. After filtration, the solvent was removed and the residue extracted into chloroform, from which it could not be isolated in pure state; it was characterised by NMR.

Bromo{1-[2-(diphenylphosphino)phenyl]-2-methoxyethyl}-(thiocyanato)gold(III), [AuBr(SCN)(sp-OMe)]. Potassium thiocyanate (10 mg, 0.10 mmol) in water (1 cm^3) was added to [AuBr$_2$(2-$Ph_2PC_6H_4CHCH_2OMe$)] (68 mg, 0.10 mmol) in acetone (20 cm^3), and the mixture stirred for 3 hours. The solvent was removed under vacuum and the pale yellow residue washed with water (40 cm^3) and extracted with chloroform (50 cm^3). The chloroform layer was separated, dried ($MgSO_4$), filtered and evaporated, leaving a yellow, oily residue which was dissolved in the minimum volume of chloroform. Diethyl ether was added to induce crystallisation, and the cloudy solution refrigerated overnight. Yield 47 mg, 67%. The complex [AuCl(SCN)(sp-Cl)] was prepared similarly.

Dicyano{1-[2-(diphenylphosphino)phenyl]-2-methoxyethyl}-gold(III), [Au(CN)$_2$(sp-OMe)]. Silver cyanide (35 mg, 0.26 mmol) was added to a solution of [AuBr$_2$(2-$Ph_2PC_6H_4CHCH_2OMe$)] (58 mg, 0.085 mmol) in acetone (15 cm^3) and the mixture stirred for 3 hours. After filtration through Celite and the removal of the solvent, a yellow oil was obtained, which was dissolved in the minimum volume of chloroform. Diethyl ether was added to induce crystallisation Refrigeration overnight gave a white solid. Yield: 74 mg, 92.1%.

Salts of the diethyldithiocarbamato{1-[2-(diphenylphosphino)-phenyl]-2-methoxyethyl}gold(III) cation, [Au(DTC)(sp-OMe)]X. *(i) X = Br.* Acetone solutions of NaDTC (33 mg, 0.147 mmol, 5 cm^3) and [AuBr$_2$(sp-OMe)] (0.10 g, 0.147 mmol, 15 cm^3) were mixed and stirred for 2 h. After filtration and removal of the solvent, the residue was extracted into chloroform and crystallised. Yield: 0.104 g, 89%.

(ii) X = Cl. The same method was used, except for a final recrystallisation from acetone. Yield: 84%.

(iii) X = BPh$_4$. Method (i) was used, adding a methanol solution of $NaBPh_4$ (1.1 mol equivalents) to the initial mixture after 2 h stirring. Yield: 73%.

2-Aminoethanethiolato{1-[2-(diphenylphosphino)phenyl]-2-methoxyethyl}gold(III) hexafluorophosphate, [Au(SCH$_2$CH$_2$-NH$_2$)(sp-OMe)]PF$_6$·CHCl$_3$. Methanol solutions of 2-sulfanylethylamine hydrochloride (16 mg, 0.14 mmol, 2 cm^3) and triethylamine (14 mg, 0.14 mmol, 2 cm^3) were mixed and added to a chloroform solution of [AuBr$_2$(sp-OMe)] (34 mg, 0.05 mmol, 15 cm^3). After stirring for 15 min and removal of the solvent, the residue was washed with water (100 cm^3) and extracted with chloroform (60 cm^3). The chloroform was removed, the residue dissolved in acetone and treated with NH_4PF_6 (6.5 mg, 0.04 mmol) in acetone (0.5 cm^3); crystallisation gave a yellow solid. Yield: 28 mg, 0.04 mmol, 92%.

Bromo{1-[2-(diphenylphosphino)phenyl]-2-methoxyethyl}-(triphenylphosphine)gold(III) tetrafluoroborate, [AuBr(PPh$_3$)-(sp-OMe)BF$_4$. An acetone solution of $AgBF_4$ (29 mg, 0.15 mmol, 2 cm^3) was added dropwise with stirring to [AuBr$_2$-(sp-OMe)] (0.10 g, 0.147 mmol) in acetone (5 cm^3). An acetone solution of PPh_3 (39 mg, 0.15 mmol, 3 cm^3) was then added and the mixture stirred for 40 min, filtered through Celite and the solvent removed. The white residue was recrystallised from chloroform–diethyl ether. The methyldiphenylphosphine complex was prepared similarly.

Crystal-structure determination of complex IX

Crystallographic data were obtained on a Nonius Mach3 diffractometer and processed with SHELXS 86 and SHELXL 93.[17]

Crystal data. $C_{24}H_{27}AuCl_3F_6NOP_2S$, $M = 856.78$, monoclinic, space group $P2_1/n$, $a = 9.570(5)$, $b = 10.896(13)$, $c = 28.29(3)$ Å, $U = 2945(5)$ Å^3, $T = 203(2)$ K, $Z = 4$, μ(Mo-Kα) = 5.506 mm^{-1}, 5495 reflections collected, 5495 unique which were used in all calculations. The final $wR(F^2)$ was 0.2199 (all data).

CCDC reference number 186/1983.

See http://www.rsc.org/suppdata/dt/b0/b002248i/ for crystallographic files in .cif format.

Table 1 ^{31}P-{^{1}H} NMR chemical shifts (δ) for gold complexes[a]

Complex	δ	Complex	δ	Complex	δ	Complex	δ
[AuCl(sp)]	27.3	[AuBr(sp)]	29.7	[AuI(sp)]	34.0	[Au(CN)(sp)]	33.8
[AuCl$_2$(sp-OMe)]	62.0	[AuBr$_2$(sp-OMe)]	60.5	[AuBr$_2$(sp-OEt)]	60.1	[AuI$_2$(sp-OMe)]	52.9
[AuCl$_2$(sp-Cl)]	60.6	[AuBr$_2$(sp-Br)]	57.4			[AuI$_2$(sp-Cl)]	51.1

[a] ^{1}H and ^{13}C data are in the supplementary material.

Table 2 NMR data for intermediates/products of reactions with iodide[a]

	[AuI$_2$(sp-OMe)] **A**	[AuI$_2$(OMe)(sp)] **B**	[AuCl(I)(OMe)(sp)] **C**	[AuI(sp)]
δ(^{31}P)	52.9	46.5	47.4	33.8
δ(C^2)	156.3 (d, 28.2)	142.8 (d, 7.4)		142.9 (d, 11.6)
δ(C^7)	71.8 (d, 8.4)	136.6 (d, 6.3)		133.7 (d, 7.4)
δ(C^8)	86.7 (d)	119.3 (s)		120.3 (s)
δ(OCH$_3$)	57.8 (s)	51.1 (s)		
δ(C*H*$_2$)	4.20, 3.57 (s)	5.55 (d, 17.05)[b] 5.02 (d, 10.9)[c]	5.53 (d, 16.8)[b] 5.36 (d, 11.8)[c]	5.60 (d, 16.9)[b] 5.29 (d, 10.7)[c]
δ(C*H*)	4.75 (s)	6.70 (dd)	7.05 (dd)	6.79 (dd)
δ(OC*H*$_3$)	2.80	3.50	3.39	

[a] Figures in parentheses are coupling constants (Hz). [b] $^3J_{trans}$. [c] $^3J_{cis}$.

Results and discussion

1 Oxidation and reduction reactions

Oxidation of gold(I). The complexes [Au(sp)X] (sp = 2-CH$_2$=CHC$_6$H$_4$PPh$_2$; X = Cl, Br or I) were prepared by standard methods. The presence of an unco-ordinated double bond is readily confirmed by NMR spectroscopy [^{1}H: characteristic pair of doublets (δ 5.3, 5.6) and multiplet δ 6.75. ^{13}C: δ(*C*H) 133.6; δ(*C*H$_2$) 120, all independent of substituents on gold; see supplementary data also] and by IR absorption at 1590 cm^{-1}. The oxidation of each complex by the corresponding dihalogen, X$_2$, was attempted in chloroform solution. With dichlorine and dibromine, oxidation at about 30 °C was complete after 24 and 48 hours respectively, and the NMR spectra of the isolated products are fully consistent with the previously proposed structures [AuX$_2$(sp-X)] (sp-X = 2-CH(CH$_2$X)C$_6$H$_4$PPh$_2$ (X = Cl or Br), see **II** in Scheme 2). The lack of a plane of symmetry through the five-membered chelate ring renders the two methylene protons inequivalent. [δ(C*H*) 5.3–5.6; δ(C*H*$_2$) 4.2–4.5 and 4.0–4.2; δ(*C*H) 70–71; δ(*C*H$_2$) 42–53; ^{31}P data are in Table 1, see supplementary data also.]

With diiodine no reaction was observed after 10 days at 30 °C; at 70 °C, some decomposition occurred but no evidence was found for any oxidised product.

The reaction of [AuBr(sp)] with dibromine was followed by ^{1}H NMR. A spectrum taken immediately after the addition of one molar equivalent of the halogen showed major signals similar to those of the gold(I) complexes, but with significant differences of chemical shift, especially for the vinylic CH$_2$ protons (to δ 4.7 and 5.8). Taken with the data presented below, this species is most likely to be the tribromogold(III) species [AuBr$_3$(sp)] (**I**, Scheme 2). Smaller signals were very similar to those of **II**.

The spectra were monitored at several time-points over the following 48 hours, during which the peaks of compound **I** steadily diminished while those of **II** grew. At 48 hours only **II** was visible.

These results thus confirm Bennett's suggested mechanism (Scheme 2).[4]

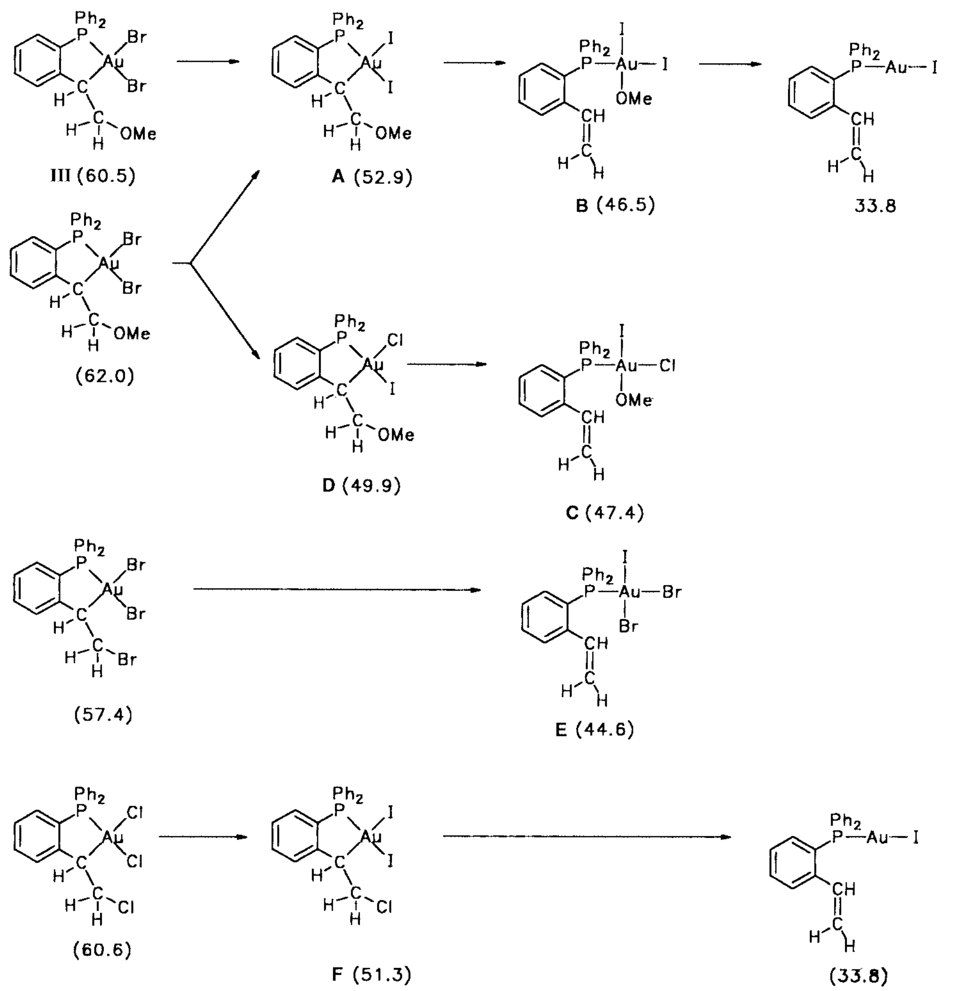
Reaction of [AuX$_2$(sp-Y)] with iodide. Since [AuI(sp)] could not be oxidised directly to [AuI$_2$(sp-I)], it was of interest to attempt the preparation of diiodogold(III) complexes indirectly, by reaction of the chloro- and bromo-complexes with iodide. Two methods were employed: (a) an acetone solution of the complex was stirred with an aqueous solution of potassium iodide for 3 hours, evaporated, and the residue extracted into chloroform; (b) a chloroform solution of the complex was treated directly with tetraethylammonium iodide. For each method, experiments were made with one or two molar equivalents of the iodide. In all cases, the ^{31}P-{^{1}H} NMR spectra of the chloroform solutions were monitored over a few days and ^{1}H and/or ^{13}C spectra recorded at some of the points. The amounts of the various species observed at various times and their NMR parameters are recorded in the supplementary tables. Although different conditions gave slightly different results, a common pattern of change is observable.

In many case (see Scheme 3), the final product was identified as the gold(I) complex [AuI(sp)]. With [AuBr$_2$(sp-OMe)], one principal intermediate was observed, **A**, whose NMR parameters are very similar to those of the starting material, the principal differences being in δ(^{31}P), δ(C^8) and δ(H^3) (Table 2). The same species was observed in reactions of [AuCl$_2$(sp-OMe)], and it is therefore presumed to be the P,C-chelated diiodo complex, [AuI$_2$(sp-OMe)]. This compound spontaneously reacts further, with eventual reduction to [AuI(sp)].

In the reaction of [AuBr$_2$(sp-OMe)] with two molar equivalents of KI a second intermediate, **B**, was observed. Its ^{31}P chemical shift (δ 46.5) is lower than those of the chelated complexes, but not as low as for the gold(I) complexes; it is not dissimilar from those of conventional phosphine complexes of the type (R$_3$P)AuX$_3$.[18] The ^{13}C and ^{1}H data show that the vinylic system is present (Table 2). Although this species was not observed in the other reactions of [AuBr$_2$(sp-OMe)], an intermediate (**C**) with very similar NMR parameters was observed in the reaction of [AuCl$_2$(sp-OMe)]. Since the methoxy-group signal is present for both **B** and **C**, we assign these species as [AuI$_2$(OMe)(sp)] and [AuCl(I)(OMe)(sp)] respectively.

One other intermediate, **D**, was observed in the reaction of [AuCl$_2$(sp-OMe)] [δ(^{31}P) 49.9]. The complexity of the mixtures in which it occurred did not allow the definition of its ^{13}C NMR spectrum, and the ^{1}H spectrum is also heavily overlapped, but we believe it to be chelated; the most likely formulation is [Au(Cl)(I)(sp-OMe)].

The reactions of [AuX$_2$(sp-Y)], (X, Y = Cl or Br) with iodide are more rapid. For X = Br, reaction with two molar equivalents of aqueous KI is complete (96%) in 3 hours, giving [AuI(sp)]. A very small quantity of a second solid was isolated with analysis corresponding to [AuI$_2$(sp-Br)] or [AuBrI$_2$(sp)]. In reaction with Et$_4$NI (one mole, in chloroform), ^{31}P NMR showed a considerable quantity of starting material remaining after 24 hours, together with species **E** (δ 44.6) whose ^{1}H spectrum indicated



Scheme 3 Reactions of $[AuX_2(sp\text{-}Y)]$ (X = Cl or Br; Y = OMe, Cl or Br) with iodide ion. Numbers in parentheses are ^{31}P chemical shifts.

that the vinylic group was present. **E** is therefore formulated as $[AuBr_2I(sp)]$, with the configuration shown in Scheme 3. Since no gold(I) species were detected, it is presumed that **E** is stable to reduction. The reaction of $[AuCl_2(sp\text{-}Cl)]$ with two molar equivalents of KI shows initial (3 h) formation of a single product, **F**, with δ 51.3, which is eventually converted into [AuI(sp)]. **F** also appears in the reaction with Et_4NI. Its ^{31}P chemical shift is in the same range as those of the other chelated derivatives and the ^1H spectrum is very similar to that of $[AuX_2(sp\text{-}Y)]$ (X, Y = Cl or Br). **F** is therefore formulated as $[AuI_2(sp\text{-}Cl)]$. The microanalysis of the solid obtained immediately after the KI treatment gave data consistent with a 1 : 1 mixture of $[AuCl_2(sp\text{-}Cl)]$ and $[AuI_2(sp\text{-}Cl)]$, which further supports this assignment.

Many of the reactions described above led to the eventual reduction of gold(III) to gold(I) with retention of co-ordination of the phosphine. The NMR spectra give, of course, no information about the secondary, oxidised product of this conversion. In cases where two molar equivalents of iodide were used, some diiodine was detected, in most cases visually, in two cases by starch–iodide treatment. Attempts to quantify this liberation proved difficult, but indicated considerably less than one mole of I_2 per mole of gold(III) reduced.

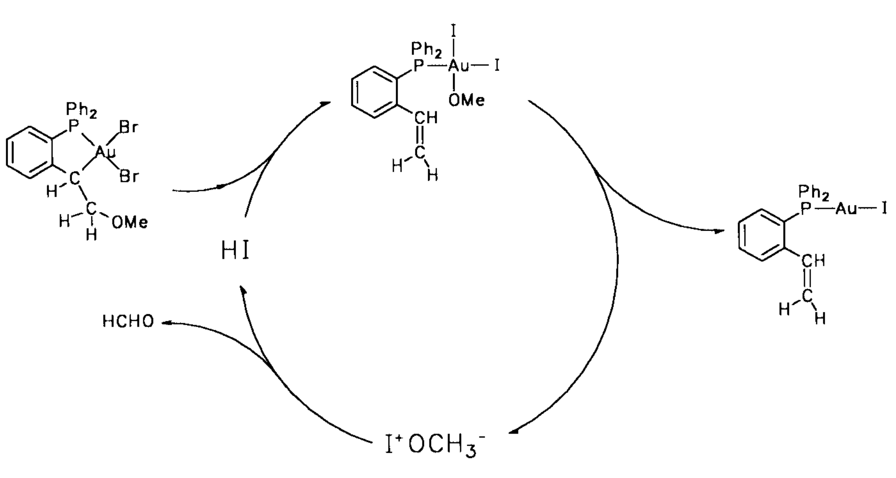
Equally, in the reactions of $[AuX_2(sp\text{-}OMe)]$, complete reduction to [AuI(sp)] occurred even when only one molar equivalent of iodide was present. In these cases, diiodine was not observed. The final gold(III) intermediate in this chain of reactions appears to be **B**, $[AuI_2(OMe)(sp)]$, which undergoes spontaneous reduction. Two possible reductive-elimination routes can be envisaged: loss of I_2 and formation of [Au(OMe)(sp)], or loss of IOMe and formation of [AuI(sp)]. The second is more attractive, in that it leads directly to the observed gold(I) product (Scheme 4). The IOMe produced would be formally an iodine(I) species, I^+OMe^-, which would be expected to decompose rapidly to HI and formaldehyde, HCH=O. The latter, being extremely volatile, would not be detected. The HI could act as a further reductant for gold(III) and it (or other free iodide present) might react with IOMe produced later to give the small quantities of diiodine observed. It is also possible that oxidation of the methoxide occurs whilst it is co-ordinated to gold(III); this is supported by the observations of reduction in reactions with alcohols reported below. However, it is clear that the other ligands can affect the rate of this reaction.

It is significant that reduction to gold(I) occurs only for complexes [AuX(Y)(Z)(sp)] (X, Y = halide; Y = halide or OMe) and when at least two of X, Y and Z are iodine: complexes **C** (Cl, I, OMe) and **E** (Br_2, I) appear to be stable. This is consistent with earlier observations[14,19] on complexes of the type $[AuX(Y)(Z)(PR_3)]$ (R = Et or Ph), where tri- and di-iodo complexes either could not be prepared or were susceptible to ready spontaneous reduction.

2 Substitution reactions

Various substitution reactions have been studied. These were complicated by often being slower than expected, but the use of longer reaction times or more forcing conditions usually led to mixtures of products, including those of reduction to gold(I). Such mixtures were difficult or impossible to separate, and characterisation often had to be made by spectroscopic analysis of the mixtures.

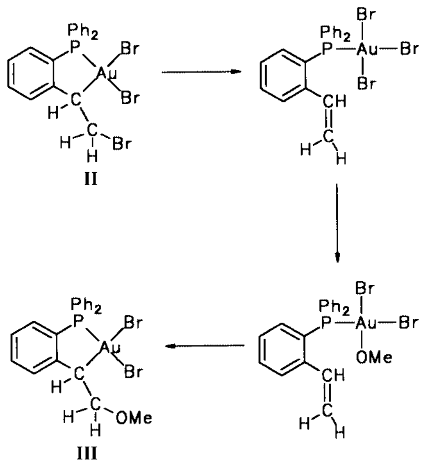
Substitution of the alkyl halide. The previous reports[2,4] mentioned that the exocyclic bromine atom of complex **II** (Scheme



Scheme 4 Proposed mechanism of reaction of [$AuBr_2$(sp-OMe)] with iodide ion.

2) could be replaced by a methoxy, ethoxy or hydroxy group to give [$AuBr_2$(sp-OR′)] (R′ = Me, Et or H) (**III**) by refluxing in the appropriate alcohol or in aqueous acetone. In our hands, only the reaction with methanol gave good yields, either with **II** or its trichloro-analogue. The best yields (>80%) were obtained with well dried methanol, and the presence of water led to degradation and production of the gold(I) complexes [AuX(sp)] (X = Cl or Br). With ethanol and Bu^tOH, yields of around 60 and 40% of [AuX_2(sp-OR′)] were obtained, in the latter case with considerable degradation. In this thesis,[16] Kneen mentions similar problems and the presence in the final reaction mixture of an unidentified ketone [ν(C=O) 1730 cm^{-1}]. It therefore seems possible that the reduction to gold(I) may involve oxidation of the alcohol. This is consistent with the results described above.

In the reactions with methanol we observed a decrease in pH as the alcoholysis proceeded. It was curious, therefore, that we could not achieve any reaction of complex **II** with sodium methoxide. With 1,2-butanediol or glycine ethyl ester ($NH_2CH_2CO_2Et$, in an excess of acetone) only the starting gold complex was recovered. With benzylamine (in acetone), reduction to [AuBr(sp)] again occurred. It therefore appears that the alcoholysis reactions are not simple nucleophilic substitutions at the pendant carbon atom. Bennett[4] has suggested that the reaction involves the alkoxo complexes [$AuBr_2$(OR)(sp)], formed by conversion of **II** back into **I** followed by substitution of a halide ligand at gold by alkoxide (Scheme 5). Our observation (Scheme 3) of this type of rearrangement gives substance to this suggestion. The recent report of the complexes $[Au(C,N,N)(OR)]^+$ (C,N,N = a 6-benzyl-2,2′-bipyridine; R = Me or Et)[12] shows that, given the right ancillary ligands, alkoxogold(III) complexes can be stable.



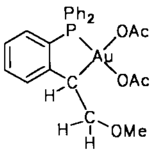
Scheme 5 Proposed mechanism of methanolysis of [$AuBr_2$(sp-Br)] (after ref. 4).

The alkoxylation reactions of gold(III) complexes derived from 2-allylphenyldiphenylphosphine are reported[4] to be reversed by the action of HBr. We found only a 10% conversion when a refluxing chloroform solution of **III** was treated with gaseous HBr over 48 hours. With an aqueous acetone solution of HBr no reaction occurred during a similar time in the cold. Partial conversion (*ca.* 50%) was achieved when [AuX_2(sp-OMe)] (X = Cl or Br), suspended in concentrated (48%) aqueous HX, was treated with concentrated H_2SO_4 at 0 °C and then refluxed for 17 (X = Br) or 48 h (X = Cl). Even though rather drastic conditions are required, the reaction presumably proceeds by migration of the alkoxy group from carbon to gold (*i.e.* the reverse of the reactions of Scheme 5).

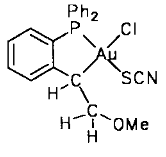
Treatment of [AuX_2(sp-OMe)] (X = Br or Cl) with $MeCO_2H$ or CF_3CO_2H led only to reduction (various ^{31}P signals in the range δ 29–39).

Substitution at gold. Various ligands have been used to replace gold-bound chloride or bromide ligands.

(i) Acetate. Reaction of [$AuBr_2$(sp-OMe)] with silver acetate gave a very light-sensitive material which was characterised only by NMR (Table 3). Previous experience[6,9,10] suggests that these data refer to [$Au(OAc)_2$(sp-OMe)] **IV**.



IV



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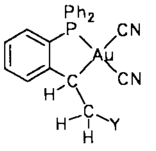

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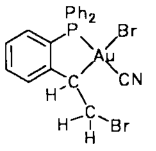


VII

(ii) Thiocyanate. The complexes [$AuCl_2$(sp-Cl)] and [$AuBr_2$(sp-OMe)] reacted cleanly with KSCN (aqueous acetone) to give [Au(X)(SCN)(sp-OMe)]. NMR data (Table 3) confirm the retention of the chelated structure, and the presence of the thiocyanato ligand is reflected in IR absorption at 2120 cm^{-1}. For X = Cl, the presence of a band at 290 cm^{-1} suggests that the chloride ligand is *trans* to carbon (**V**).

Reactions with an excess of AgSCN showed the presence of a second component [δ(^{31}P) 64.6], presumed from microanalyti-

Table 3 NMR data for substituted complexes[a]

	$[Au(OAc)_2(sp\text{-}OMe)]$[b]	$[AuCl(SCN)(sp\text{-}Cl)]$	$[AuBr(SCN)(sp\text{-}OMe)]$	$[Au(CN)_2(sp\text{-}Cl)]$	$[Au(CN)_2(sp\text{-}Br)]$
$\delta(^{31}P)$	47.7	62.7	63.5	54.6	53.8
$\delta(C^2)$	154.9 (24.2)		155.2 (26.1)		154.0 (25.3)
$\delta(C^7)$	59.3 (4.2)		79.4		70.3
$\delta(C^8)$	77.0		78.8 (5.8)		41.5
$\delta(OCH_3)$	57.6		58.1		
$\delta(CH)$	4.98	4.82	4.64	5.01	5.29
$\delta(CH_2)$	3.80, 3.29	4.28, 4.09	4.04, 3.87	4.54, 4.22	4.57, 5.29
$\delta(OCH_3)$	3.04		2.82		
$\delta(CN)$					129.3

[a] Figures in parentheses are coupling constants (Hz). [b] $\delta(CH_3CO_2)$ 22.8, 23.0; $\delta(CH_3CO_2)$ 174.7, 174.8; $\delta(CH_3CO_2)$ 1.76, 2.10.

Table 4 NMR data for substituted complexes[a]

	$[Au(DTC)\text{-}(sp\text{-}OMe)]Br$	$[Au(DTC)\text{-}(sp\text{-}OMe)]Cl$	$[Au(DTC)\text{-}(sp\text{-}OMe)]BPh_4$[b]	$[Au(mea)\text{-}(sp\text{-}OMe)]PF_6$	$[AuBr(PPh_3)\text{-}(sp\text{-}OMe)]BF_4$	$[AuBr(PMePh_2)\text{-}(sp\text{-}OMe)]BF_4$[c]
$\delta(^{31}P)$	56.2	56.2	56.4	57.4	65.7, 36.6 (420)	64.9, 28.9 (428)
$\delta(C^2)$	155.6 (27.4)	155.5 (27.3)	155.8 (27.4)		143.0	
$\delta(C^7)$	64.5	63.4	65.6		76.0 (4.2)	67.8
$\delta(C^8)$	79.3	79.2	79.4		78.9	70.5
$\delta(OCH_3)$	59.0	59.0	59.3		58.7	
$\delta(CN)$	198.3	198.3	198.7			
$\delta(CH_2CH_3)$	47.6, 49.9	47.4, 47.5	47.3, 47.5			
$\delta(CH_2CH_3)$	13.1, 13.2	12.9, 13.0	13.0, 13.1			
$\delta(CH)$	4.88 (11)	4.88	4.53 (7.2)	4.1	4.35	4.61
$\delta(CH_2)$	3.95, 3.78	3.95, 3.78	3.83, 3.63	3.4, 3.4	3.22, 3.05	3.43, 3.14
$\delta(OCH_3)$	3.04	3.04	3.21		2.68	
$\delta(CH_2CH_3)$	3.81, 3.92	3.81, 3.92	3.40, 3.50 (4.8)			
$\delta(CH_2CH_3)$	1.40, 1.45	1.40, 1.45	1.18, 1.24 (4.8)			

[a] Figures in parentheses are coupling constants (Hz). [b] $\delta(SCH_2)$ 5.3; $\delta(CH_2N)$ 2.85. [c] $\delta(CH_3PPh_2)$ 25.9 (68); $\delta(CH_2PPh_2)$ 2.67 (11.7, 8.2).

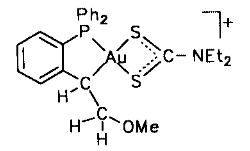
cal data to be the bis-thiocyanato complex. A weak IR absorption at 2080 cm^{-1} is seen in addition to the stronger band at 2120 cm^{-1}.

(iii) Cyanide. The reaction of $[AuCl_2(sp\text{-}Cl)]$ or $[AuBr_2(sp\text{-}Y)]$ (Y = Br or OMe) with AgCN gave the disubstituted complexes **VI** directly [$\delta(^{31}P)$ 54.6 (Y = Cl), 53.8 (Br), 54.8 (OMe)]. The solubility for Y = OMe was very poor, and other NMR data could not be obtained; data for Y = Cl (also of limited solubility) and Br are in Table 3. Only a single, very weak ^{13}C signal attributable to co-ordinated cyanide could be discerned (for Y = Br). All complexes showed two IR absorptions assignable as $\nu(C\equiv N)$ 2170, 2215 (Y = Cl), 2150, 2205 (Y = Br), 2129, 2200 cm^{-1} (Y = OMe).

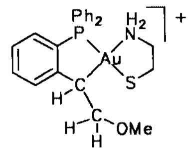
Reactions with aqueous sodium or potassium cyanide were more complex. For $[AuBr_2(sp\text{-}Br)]$ with an excess of NaCN, reduction to $[Au(CN)(sp)]$ occurred cleanly; the product was characterised by independent synthesis of the gold(I) complex (Supplementary data). With a single molar equivalent of KCN, in dilute solution, the ^{31}P NMR spectrum showed a mixture of starting material (δ 57.5) with $[Au(CN)_2(sp\text{-}Br)]$ (δ 53.8) and $[Au(CN)(sp)]$ (δ 33.8); a fourth signal (δ 54.4), clearly belonging to a chelated gold(III) complex is most likely to be $[AuBr(CN)(sp\text{-}Br)]$ with structure **VII**.

The complex $[AuBr_2(sp\text{-}OMe)]$ reacted rapidly with aqueous cyanide, and the only ^{31}P signal observed after work-up corresponded to the phosphine oxide, sp=O (δ 32.1), identified by comparison with a sample prepared independently from free sp.

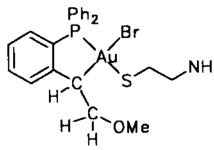
(iv) Diethyldithiocarbamate. The complexes $[AuX_2(sp\text{-}OMe)]$ (X = Cl or Br) reacted readily with one molar equivalent of sodium diethyldithiocarbamate (NaDTC) in acetone to give $[Au(DTC)(sp\text{-}OMe)]X$. The addition of sodium tetraphenylborate gave $[Au(DTC)(sp\text{-}OMe)]BPh_4$. These materials have essentially similar NMR parameters (Table 4), showing that the halide in the first two products is not co-ordinated; small differences in chemical shifts suggest some ion pairing in the $CDCl_3$ solution. The spectra indicate non-equivalence of the DTC ethyl groups, as expected for chelation of the DTC group (**VIII**). Reaction with two molar equivalents of NaDTC gave the same product together with a trace of a known[20] form of the gold(I) complex $[Au_4(DTC)_4]_n$ (identified crystallographically); we were not able to introduce a second DTC ligand.



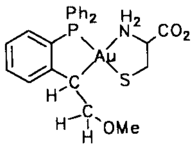
VIII



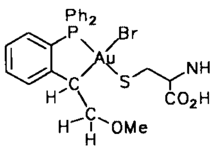
IX



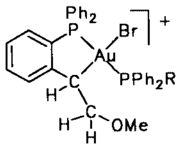
X



XI

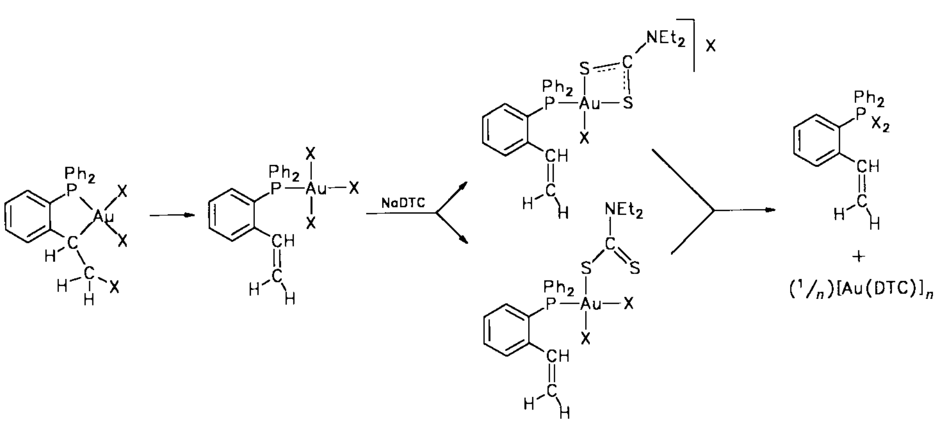


XII



XIII

As before, $[AuBr_2(sp\text{-}Br)]$ reacted more rapidly and underwent reduction, at all reactant ratios. The ^{31}P NMR spectra



Scheme 6 Proposed mechanism for reduction of [AuX_2(sp-X)] (X = Cl or Br) by dithiocarbamate.

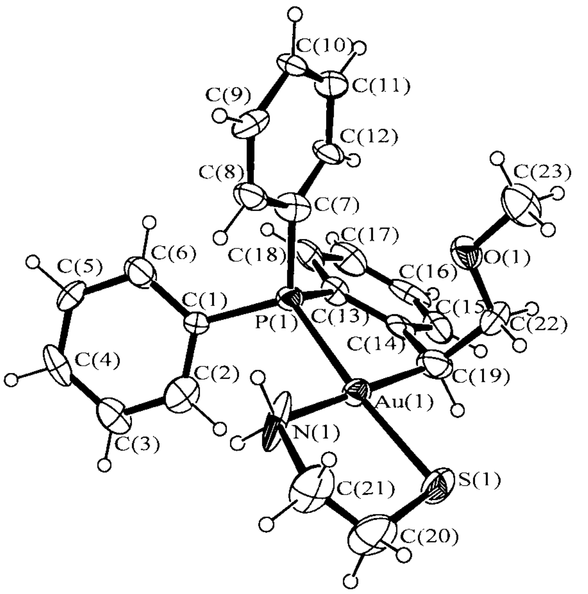


Fig. 1 Structure of the cation [Au(mea)(sp-OMe)]$^+$.

Table 5 Significant bond lengths (Å) and angles (°) for [Au(mea)-(sp-OMe)]PF_6

Au(1)–P(1)	2.296(5)	P(1)–Au(1)–N(1)	94.7(6)
Au(1)–S(1)	2.285(6)	N(1)–Au(1)–S(1)	91.2(6)
Au(1)–N(1)	1.89(2)	P(1)–Au(1)–S(1)	174.0(2)
Au(1)–C(19)	2.04(2)	C(19)–Au(1)–P(1)	84.0(6)
		C(19)–Au(1)–S(1)	90.2(6)
		C(19)–Au(1)–N(1)	177.4(7)

showed two signals (δ 29.7, 32.9), and the ^1H spectra indicated the presence of two vinylic systems and the absence of the chelated form. By comparison with a sample prepared independently, the species with $\delta(^{31}P)$ 32.9 was identified as the phosphine oxide, sp=O. None of the signals in the ^1H spectrum of the reaction mixture corresponded to the other possible oxidised product, the thiuram disulfide $Et_2NC(S)SSC(S)NEt_2$; this was confirmed by adding the authentic thiuram to the NMR tube. Crystals formed in the NMR tubes were shown crystallographically to be either $[Au_4(DTC)_4]_n$ or $[Au(DTC)]_2$,[21] depending on the reaction conditions. These observations are consistent with the reactions shown in Scheme 6, involving rapid dechelation of the phosphine, which must occur before co-ordination of the DTC (at least in its chelated form), followed by reductive elimination of the phosphine dibromide and its hydrolysis by traces of adventitious moisture. However, the second ^{31}P signal (δ 29.7) appears to be due to [AuBr(sp)] (the signal for [Au(DTC)(sp)], prepared independently, is at δ 31.1). Evidently, there is also a pathway which results in reduction of gold without reaction of the phosphine ligand and without formation of thiuram disulfide; we are at present unable to propose a satisfactory mechanism.

(v) With 2-sulfanylethylamine. The complex [$AuBr_2$(sp-OMe)] reacted rapidly with $HSCH_2CH_2NH_2$ (Hmea, 3 molar equivalents in methanol) to give two products with ^{31}P chemical shifts of δ 57.4 (**IX**, major) and 53.9 (**X**, minor). Addition of NH_4PF_6 to the solution allowed crystallisation of the major component, whose structure was determined by X-ray crystallography. The cation is [Au(mea)(sp-OMe)]$^+$, the structure of which is shown in Fig. 1; significant bond distances and angles are in Table 5. Both the phosphine and the sulfanylamine are chelated and the thiolate group of the latter is *trans* to the phosphorus atom. The only direct comparisons that can be made are with [$AuBr_2$(sp-Br)] and [$AuBr_2$(ap-Br)] (ap-Br = 2-($BrCH_2CHCH_2$)PPh_2), which have rather longer Au–C [2.10(3), 2.13(4) Å] and shorter Au–P bond lengths [2.26(1), 2.28(1) Å].[3]

The second complex, **X**, was observed in greater relative proportion when only one molar equivalent of Hmea was used (reaction time 3 h). Unfortunately, the reaction mixture contained also the starting material, complex **IX** described above and the gold(I) complex [AuBr(sp)]. Shorter reaction times gave very little reaction, longer gave complete reduction to [AuBr(sp)]. It seems likely that **X** is [Au(Br)(mea)(sp-OMe)], containing an S-monodentate mea ligand; a similar intermediate was isolated in the reaction of [$AuCl_2$(L′)] with Hmea [L′ = 2-(2-pyridyl)phenyl].[10]

(vi) With L-cysteine and L-penicillamine (3-sulfanyl-D-valine). Reaction of [$AuBr_2$(sp-OMe)] with L-cysteine (one molar equivalent, plus two molar equivalents of Et_3N, in water) gave a product with microanalysis corresponding to the replacement of one bromide by a deprotonated L-cysteine. ^{31}P NMR showed that two species were present (δ 56.9, 53.2). The same signals, accompanied by those of starting material and/or reduced complexes, were seen under a variety of reaction conditions. We were unable to separate the complexes. In view of the similarity of chemical shifts to those of the sulfanylethylamine complexes **IX** and **X**, they are assigned analogous structures, **XI**, **XII** (in the presence of Et_3N, **XII** is presumed to have a deprotonated carboxylate group). Similar results were obtained with L-penicillamine.

(vii) With tertiary phosphines. According to the ^{31}P NMR, [$AuBr_2$(sp-OMe)] remains unchanged in the presence of either Ph_3P or $MePh_2P$. When $AgBF_4$ was added before the phosphine, rapid reaction occurred and, with either phosphine, the NMR showed two doublets with equal coupling constants. The magnitude of the coupling (420 Hz for Ph_3P, 428 Hz for Ph_2MeP) shows that the incoming phosphine is *trans* to the original phosphine (**XIII**). The ^{13}C and ^1H data confirm that chelation is retained (Table 4). The complex [$AuBr_2$(sp-Br)] undergoes rapid reduction on addition of either phosphine.

Conclusion

The chemistry described here is both fascinating and difficult. It is enormously complicated by the ready reduction of a variety of gold(III) complexes to the gold(I) complexes [AuX(sp)], *via* the rupture of gold–carbon bonds, and this frequently prevented the isolation of materials which might have been expected to be quite stable.

The results obtained largely confirm the early postulates of Bennett,[3,4] in particular the facile and reversible addition of Au–X (X = Cl, Br or I) across a carbon–carbon double bond (**I** $\longleftrightarrow$ **II**, Scheme 2). This is analogous to the interconversions of a metal–hydride–alkene/metal–alkyl system (insertion/β elimination), although these are not known for gold(III). The corresponding reaction of an Au–OMe bond is slower, and the reverse reaction is in this case much more difficult, presumably owing to the greater strength of the carbon–oxygen bond. It is now clear that the reverse, dechelation reactions (*e.g.* **III** $\longrightarrow$ **A**, Scheme 3) may sometimes occurs spontaneously, but it is by no means obvious what conditions are required. The dechelation is certainly a necessary step in the reduction reactions, and these reactions appear both to be very sensitive to the nature of the ligands and to have a variety of mechanisms.

Ligand-substitution reactions with [AuX$_2$(sp-Y)] (X = Cl or Br; Y = Cl, Br or OMe) always lead to replacement of the halide *trans* to phosphorus. Since both structural and IR evidence point to a higher *trans* effect/influence for the carbon ligand, it seems likely that, as with the C,N chelates, initial reaction takes place *trans* to the carbon, and is rapidly followed by rearrangement to the thermodynamically more stable isomer.[22]

For some C,N complexes, reaction with an additional ligand (*e.g.* a tertiary phosphine) leads to dechelation by displacement of the N-donor group; only the most strongly bound N-donor groups are able to resist (*e.g.* NMe$_2$). With the dithiocarbamate anion, complexes of the type [Au(C,N)(DTC)]$^+$ and [Au(C,N)(DTC)$_2$] may be obtained; in the former both ligands are chelated but in the latter the C,N ligand is monodentate (C-bound) and the DTC ligands are both mono- and bi-dentate in a fluxional system. In the present case it is possible to introduce only a single DTC ligand, which chelates. There seems no *a priori* reason against a product of the type [Au(DTC)$_2$(sp-Y)], containing two monodentate DTC ligands. Evidently the binding of a second DTC is prevented by the reluctance of the phosphine donor group to dissociate. In the C,N case the mechanism for attack by a second DTC must involve the rupture of the Au–N bond rather than the Au–S(DTC) bond.

It was not found possible to achieve substitution of the exocyclic, carbon-bound halide or methoxide. This argues strongly against direct nucleophilic attack at carbon, *e.g.* in the conversion of [AuBr$_2$(sp-Br)] into [AuBr$_2$(sp-OMe)], and renders likely the original suggestion[4] that substitution occurs at gold *via* a de-insertion/re-insertion mechanism (Scheme 5). However, little evidence was obtained for the occurrence of substitution in the [AuX$_3$(sp)] form; such substitution would, of course, be expected to be *trans* to the phosphorus and would not put the incoming ligand in a position to attack the carbon–carbon double bond.

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