Electrospray ionization mass spectra of the reactions of NaAuBr(4) and related aurates with nucleophiles

Electrospray ionization mass spectra of the reactions of NaAuBr₄ and related aurates with nucleophiles

Additional supporting information may be found in the online version of this article at the publisher's web site.

Dear Sir,

Electrospray ionization mass spectra in the negative ion mode, ESI(−)MS, of aqueous solutions of $AuBr_3$ at different pH values have been reported by us,[1] confirming the rapid equilibria (speciation) that were observed by spectrophotometry:[2–4] $AuBr_4^-$ and $[AuBr_3(OH)]^-$ predominate at pH 4 and $[AuBr_2(OH)_2]^-$ in neutral solutions. Independently, other authors have reported similar ESI mass spectra of $[AuCl_n(OH)_{4-n}]^-$.[5] Thus, gold seems to be unique among all the elements of the periodic table, not only because of the properties of the metal, known from the beginning of the mankind, and of the gold nanoparticles,[6,7] but also because gold(III) salts do not precipitate easily $Au(OH)_3$ under neutralization, particularly in the presence of anions such as bromide or cyanide.[8,9] With the aim of uncovering further features of aurate(III) ions, we carried out a series of MS experiments that are reported for the first time: (1) the characterization of commercially available samples of NaAuBr₄ and NaAuCl₄ at different pH values, (2) the detection by ESI(−)MS of the exchanges of ligands (Cl/Br/CN) in aurates and (c) a study of the reactivity (or lack of reactivity) of NaAuBr₄ with alcohols, phenols, carbonyl compounds, 1,3-dicarbonyl or 1,3-dicarboxyl compounds, and oximes, also followed by ESI(−)MS.

We first analyzed by ESI(−)MS aqueous solutions of NaAuBr₄ · H₂O and NaAuCl₄ · 2H₂O at different pH values. The spectra were recorded with an Agilent LC/MSD TOF instrument set under the following conditions: 20-V fragmentation voltage, 3500-V capillary voltage, 3 ml/min flow and capillary temperature of 350 °C, with N₂ as the nebulization gas at 20 psi. Several spectra were also registered at lower temperatures (150 °C) with the same results (although the sensitivity decreased). The solutions were prepared in milli-Q water, at 0.10 M concentrations, and were allowed to equilibrate until the pH value (Crison pH-meter) was stable. They were then diluted (1:100) with ultrapure water and injected immediately. At the beginning of this work, we examined the effect of this dilution (0.001 M); in spite of the expected fact that the pH values were closer to 7, the spectra were identical to those at 0.10 M. The halido-to-hydroxido exchanges must be slowed down by dilution (with initial reaction rates 10^{-4} times lower), which explains that the relative intensities of the peaks were practically the same as those in the equilibria at 0.10 M.

In ultrapure water, the commercially available samples of NaAuBr₄ · H₂O (from Alfa Aesar and from Strem) and NaAuCl₄ · 2H₂O (from Aldrich) have pH values below 3 (1.81, 1.70 and 2.49, respectively, at 0.1 M), and around one equiv of NaOH had to be added to neutralize the solutions to pH 7. By ESI(−), both samples of 'NaAuBr₄ hydrate' in pure water showed only an intense $AuBr_4^-$ peak (see Fig. 1a), with insignificant amounts of Br^- (or aggregates containing this anion). Thus, samples sold as sodium tetrabromoaurate–hydrate may contain high percentages of $HAuBr_4$; this deserves a warning because some reactions assumed to be catalyzed by these gold(III) species could be actually promoted by the protons of $HAuBr_4$ that contaminated NaAuBr₄ · H₂O. On the other hand, the solutions of NaAuCl₄ · 2H₂O in pure water showed some hydrolysis to $H[AuCl_3(OH)]$ (Fig. 1c), and NaCl (signals of $[NaCl_2]^-$ were detected), which partially explains their acidic pH; again, it is worth noting that some reactions reported to be catalyzed by $AuCl_4^-$ species could have been promoted by $H[AuCl_3(OH)]$ present in samples of NaAuCl₄ · 2H₂O. The addition of NaOH to these AuX_4^- samples, up to pH 8.5, caused the replacement of some halide ligands, but $AuBr_4^-$ still remained (Fig. 1b), whereas $AuCl_4^-$ disappeared almost completely (Fig. 1d; isotopic distributions are in agreement with the $^{35}Cl/^{37}Cl$ ratio). Apparently, chloro/chorido ligands were replaced easily by the hydroxo/hydroxido ligands. In spite of that, species $[AuCl_n(OH)_{4-n}]^-$ were clearly observed. In sharp contrast, when we neutralized analogous aqueous solutions of trivalent cations other than Au^{III}, such as $FeBr_4^-/Fe_2Br_7^-$, $InBr_4^-/In_2Br_7^-$ and $LaBr_4^-$, the ESI(−) signals were lost, due to the immediate formation of insoluble hydroxides or hydrated oxides.

The addition of NaBr to a neutral aqueous solution of NaAuCl₄ (yellow) gave rise to the appearance of $AuBr_4^-$ and/or tribromoaurate-containing species (characteristic wine-red color and typical ESI spectra). It was not necessary to add a large excess of bromide ions to shift the equilibrium to the right: with only 200 mol % of NaBr, albeit all species $[AuBr_nCl_{4-n}]^-$ species were detected, $AuBr_4^-$ was already relatively abundant (see Fig. 2a); with 400 mol % of NaBr, most the chloride ions had been replaced by bromide ions ($AuBr_2Cl_2^-$ not observed). More outstanding was the change observed by addition of NaCN to the wine-red solutions of $AuBr_4^-$, since the color faded immediately with only 200 mol % of cyanide ions (Fig. 2b); with ≥300 mol %, $Au(CN)_4^-$ was the exclusive species detected. Thus, aurates with mixed ligands (depicted within brackets in Scheme 1) are not particularly favored. Moreover, aurates with several bromo/bromido ligands are more stable than their analogous Cl complexes, and cyano/cyanido–aurates even more (in fact, we could not replace cyano ligands by hydroxide ions, or any other ligands). Some of these reactions were studied

* *Correspondence to: Jaume Vilarrasa, Department of Organic Chemistry, Faculty of Chemistry, University of Barcelona, Av. Diagonal 645, E-08028 Barcelona, Catalonia, Spain. E-mail: jvilarrasa@ub.edu*
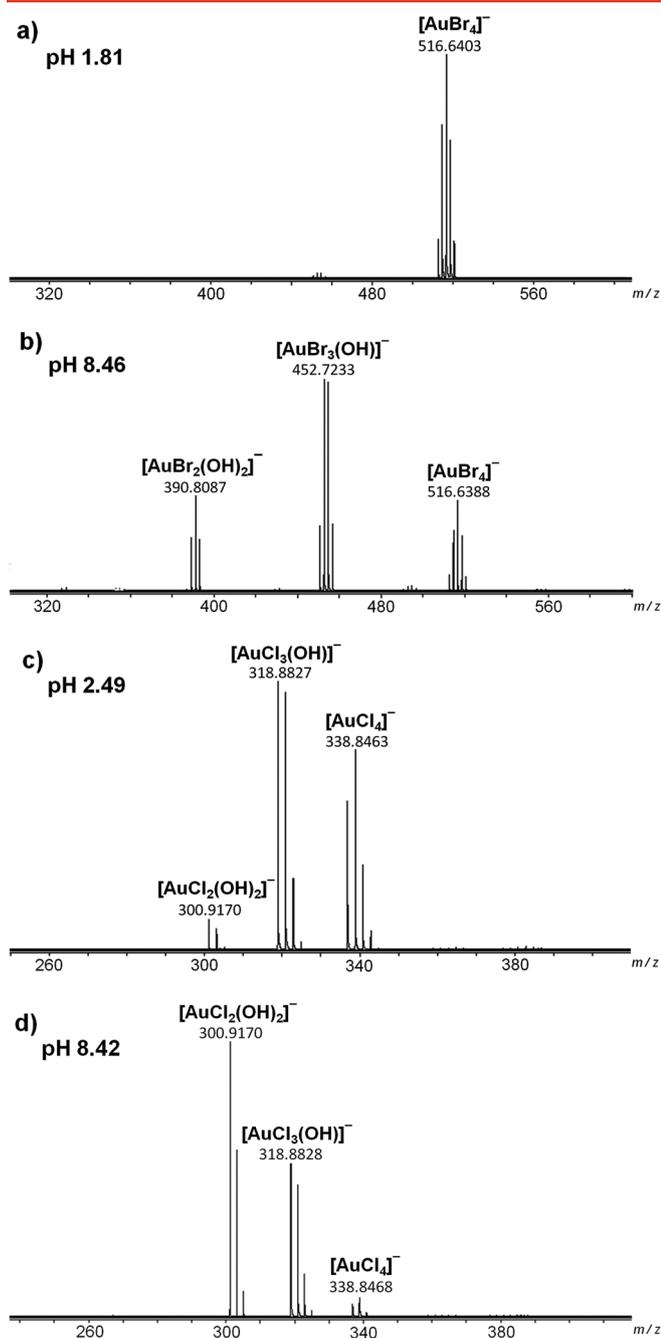
Figure 1. ESI(−) mass spectra of NaAuBr₄: (a) without neutralization and (b) after neutralization with NaOH till pH 8.46. ESI(−)MS of NaAuCl₄ (c and d).

Figure 2. ESI(−) spectra of aqueous solutions from: (a) $AuCl_4^- + 2\ Br^-$; (b) $AuBr_4^- + 2\ ^-CN$.

spectrophotometrically years ago, with results[2–4] that ESI(−)MS has now confirmed. We also show that ESI(−)MS is a quick technique to gain further insight into these exchanges. Even though the study of the rates and/or equilibrium constants of formation of these anionic complexes is outside our interests, ESI(−)MS not only allows for the reliable characterization of the species involved (speciation) but also might provide kinetic information and their relative stability order.

Once the main aurate species in solution were established, we examined their possible reactions with alcohols, phenols, aldehydes, ketones and 1,3-dicarbonyls (activated methylene compounds). Most experiments were carried out with bromoaurates
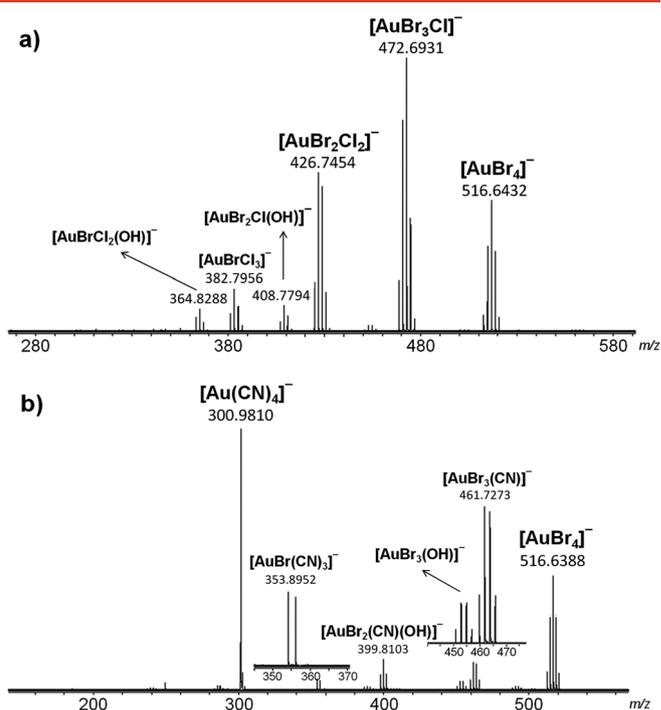
rather than with chloroaurates or cyanoaurates. We chose bromoaurates because their neutral and basic solutions can be stored for a long time while chlorohydroxoaurates decompose (with formation of Au^I and/or Au precipitates), because cyanoaurates are so stable that they do not react with nucleophiles and because bromoaurates have been hardly investigated. In aqueous CH₃CN or in aqueous THF, at room temperature (RT), we observed that simple alcohols, aldehydes and ketones did not react with $AuBr_4^-$ or with $[AuBr_n(OH)_{4-n}]^-$. This was surprising at first sight, as primary and secondary alcohols are oxidized to aldehydes and ketones, respectively, by $[AuCl_3(OH)]^-$ and $AuCl_4^-$ in acetate-buffered aqueous media[10]; the explanation lies again in the greater kinetic and thermodynamic stability, in aqueous solutions, of $[AuBr_n(OH)_{4-n}]^-$ with regard to $[AuCl_n(OH)_{4-n}]^-$. However, on heating in non-aqueous media, bromoaurates enter more easily in redox processes; in fact, heating of $[Et_4N][AuBr_4]$ with acetone was used to prepare $[Et_4N][AuBr_2]$ (with formation of bromoacetone).[11]

Phenol reacted with NaAuBr₄ (at pH ≤ 7.0, where $AuBr_4^-$ predominates), with disappearance of the wine-red color and bromination at the *para* position of the hydroxy group. When more NaAuBr₄ was added, up to an equimolar ratio, dibrominated phenol (2,4-dibromophenol, according to the ¹H NMR spectrum) and tribrominated phenol (2,4,6-tribromophenol) were then predominant by ESI(−)MS. Thus, redox processes were more rapid than exchange of ligands, under these conditions. However, when the $AuBr_4^-$ solutions were previously set to pH 9.5 (that is, when $[AuBr_2(OH)_2]^-$ and $[AuBr_3(OH)]^-$ were the major species in the medium, with a small percentage of $AuBr_4^-$ remaining) and phenol was then added in CH₃CN/H₂O (as phenolate ion, to maintain pH 9), mainly $[AuBr(OH)_2(OPh)]^-$ was detected by ESI(−)MS (Fig 3a), with disappearance of $[AuBr_n(OH)_{4-n}]^-$ ($n = 2$ and 3). Also, 4-methylphenol (*p*-cresol), when treated with $[AuBr_n(OH)_{4-n}]^-$ ($n = 2-4$), maintaining pH 9, chiefly gave $[AuBr(OH)_2(OPh^{4Me})]^-$.
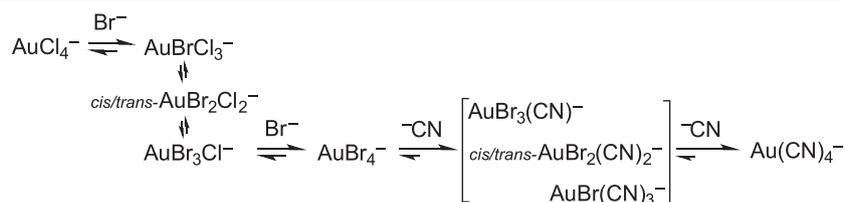
Scheme 1. Equilibria (simplified) among $[AuX_nY_{4-n}]^-$ complexes.

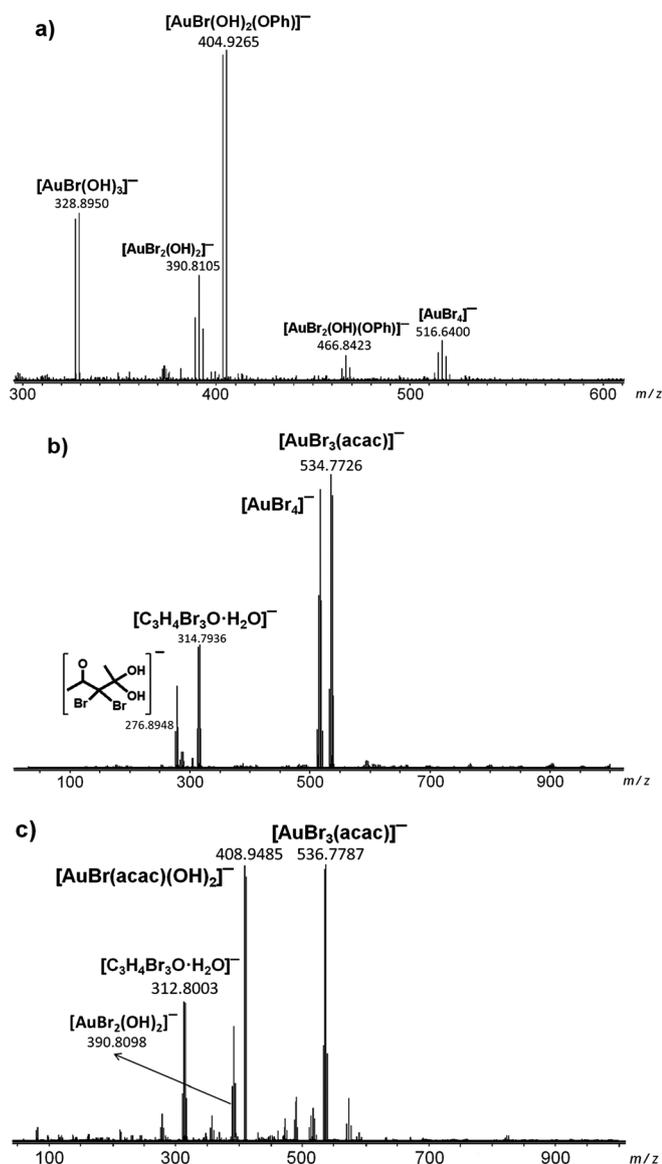**Figure 3.** ESI(−) mass spectra of: (a) phenol and $[AuBr_n(OH)_{4-n}]^-$ ($n = 2$–4) at pH 9; (b) acetylacetone and $AuBr_4^-$ (pH 7); the 'quartet' at m/z 310–316 is a fragmented species (tribromoacetone–hydrate derivative, see SI); (c) acetylacetone and $[AuBr_n(OH)_{4-n}]^-$ ($n = 2$–4) at pH 9.

2,4-Pentanedione (acetylacetone, acacH) also reacted with $AuBr_4^-$ (pH 7). To the best of our knowledge, there is only one related case reported, namely, the reduction of $Bu_4N[AuCl_4]$ to $Bu_4N[AuCl_2]$ by acetylacetonate.[12] ESI(−)MS indicated that $AuBr_4^-$ and acacH gave $[AuBr_3(acac)]^-$ (Fig. 3b). Thus, unlike the case of phenol, the expected complex could be observed at

neutral pH values, but 30 min later $AuBr_4^-$ had disappeared while fragmentation product(s) became predominant ($[C_3H_4Br_3O \cdot H_2O]^-$, tribromoacetone derivative(s) arising from Br transfer and deacetylation, see Supporting Information, SI). Bromination of the active methylene group was confirmed by NMR spectroscopy, while a gold mirror was formed in the vial. When the reaction was re-examined at pH 9 (that is, with $[AuBr_n(OH)_{4-n}]^-$, $n = 2$–4, plus acac$^-$), in CH_3CN/H_2O, the main anionic species were $[AuBr_3(acac)]^-$ and $[AuBr(acac)(OH)_2]^-$ (Fig. 3c).

In other words, acac-containing complexes with three and one bromo ligands were relatively more stable. Ionic complex $[AuBr_3(acac)]^-$ can only come from $AuBr_4^- + acac^-$, while $[AuBr(OH)_2(acac)]^-$ must come from $[AuBr_2(OH)_2]^- + acac^-$ and from $[AuBr_2(OH)(acac)]^- + OH^-$. Diethyl malonate behaved similarly to acacH.

We also examined the reaction of $NaAuBr_4$ with ketoxime $PhCH_2CH_2C(=NOH)CH_3$ (3-phenyl-2-butanone oxime) by ESIMS. We had investigated[1] reactions of oximes with AuX_3 but not with $NaAuBr_4$, which we report here for the first time. At acidic pH ($NaAuBr_4 + HAuBr_4$), there was no replacement of ligands, as well as no redox processes (unlike the previous cases of phenols and active methylene compounds, which may be explained by the greater tendency of phenol and acacH to undergo C-bromination). At pH 6.3 ($NaAuBr_4$), pH 8.5 (equilibrium mixture shown in Fig. 1b) and pH 9.5 (where, as already indicated, $[AuBr_2(OH)_2]^-$ and $[AuBr_3(OH)]^-$ were the major species), the substitution of one oximato for one bromo ligand was observed. All these aurate species did react, although $AuBr_4^-$ did it more slowly. As in the cases of phenols and acetylacetone, only one ligand was incorporated, even with a large excess of oxime at basic pH.

Apparently, in aqueous media (aqueous CH_3CN or THF), only organic compounds with pK_a values below 12–13, such as phenols, active methylene compounds and oximes, are capable to replace one and only one bromo ligand of these Au^{III} complexes at RT, but their behavior pattern is different. To summarize: (1) phenols are brominated with $AuBr_4^-$ while phenolates replace bromo ligands of $[AuBr_n(OH)_{4-n}]^-$ more rapidly than those of $AuBr_4^-$, (2) acacH does react with $AuBr_4^-$ with subsequent bromination, while acac$^-$ gives rise mainly to a ligand exchange at basic pH, with all Au^{III} species, and (3) $[AuBr_2(OH)_2]^-$ and $[AuBr_3(OH)]^-$ are more reactive than $AuBr_4^-$ with oximes. Even though it could be expected that moderately hard anions (phenolates), delocalized OCCHCO anions and NOH groups (possible α-effect) or the corresponding oximato ligands (=N–O$^-$) would not react similarly, the chameleonic behavior of the bromoaurates is remarkable. Additional studies will be undertaken to gain more insight into their reactivity against organic functional groups. We also hope to report in the near future practical applications of $NaAuBr_4$ as a catalyst in the field of organic synthesis.

In conclusion, we have elucidated by ESI(−)MS, for the first time, the nature and approximate ratios of aurates $[Au^{III}X_nY_m]^-$ that are quickly generated when $NaAuX_4$ is mixed with ions Y^- (where X and Y are Cl, Br, CN and/or OH ligands). The solubility

and stability at different pH values of bromohydroxoaurates are exceptional. Also for the first time, reactions of $NaAuBr_4$ with several types of organic compounds, including phenols, active methylene compounds and oximes have been followed by ESI(−)MS. Species $AuBr_4^-$, $[AuBr_3(OH)]^-$ and $[AuBr_2(OH)_2]^-$ do not react similarly with these nucleophiles. Unlike the $[AuBr_n(OH)_{4-n}]^-$ ionic complexes, species such as $[AuBr_2(OR)_2]^-$ and $[AuBr(OR)_3]^-$ (with two o three alkoxido, phenolato, acetylacetonato or oximato ligands) have not been detected.

Yours,

Carles Isart,[a] Jordi Burés[a,b] and Jaume Vilarrasa[a]*

[a]Department of Organic Chemistry, Faculty of Chemistry, University of Barcelona, Av. Diagonal 645, E-08028 Barcelona, Catalonia, Spain

[b]Department of Chemistry, Imperial College, London SW7 2AZ, UK

References

[1] C. Isart, D. Bastida, J. Burés, J. Vilarrasa. Gold(III) complexes catalyze deoximations/transoximations at neutral pH. *Angew. Chem. Int. Ed.* **2011**, *50*, 3275–3279.

[2] A. Usher, D. C. McPhail, J. Brugger. A spectrophotometric study of aq. Au(III) halide-hydroxide complexes at 25-80 °C. *Geochim. Cosmochim. Acta* **2009**, *73*, 3359–3380, and references cited therein.

[3] I. V. Mironov, E. V. Makotchenko. The hydrolysis of $AuCl_4^-$ and the stability of aquachlorohydroxocomplexes of gold(III) in aqueous solution. *J. Solution Chem.* **2009**, *38*, 725–737.

[4] V. Vasic, S. Premovic, M. Cakar, B. Radak, G. Milovanovic. Spectrophotometric investigations of the reaction between gold(III) and potassium iodide. *J. Serbian Chem. Soc.* **2000**, *65*, 345–352.

[5] J. C. Marcum, S. H. Kaufman, J. M. Weber. Gas-phase experiments on Au(III) photochemistry. *J. Phys. Chem. A* **2011**, *115*, 3006–3015.

[6] Very recent review: P. Zhao, N. Li, D. Astruc. State of the art in gold nanoparticle synthesis. *Coord. Chem. Rev.* **2013**, *257*, 638–665.

[7] Very recent review: E. C. Dreaden, M. A. El-Sayed. Detecting and destroying cancer cells in more than one way with noble metals and different confinement properties on the nanoscale. *Acc. Chem. Res.* **2012**, *45*, 1854–1865.

[8] S. Syed. Recovery of gold from secondary sources–A review. *Hydrometallurgy* **2012**, *115–116*, 30–51.

[9] C. F. Baes, R. E. Mesmer. The Hydrolysis of Cations. Wiley: New York, **1976**.

[10] B. Pal, P. K. Sen, K. K. S. Gupta. Reactivity of alkanols and aryl alcohols towards tetrachloroaurate(III) in sodium acetate-acetic acid buffer. *J. Phys. Org. Chem.* **2001**, *14*, 284–294.

[11] P. Braunstein, R. J. H. Clark. Preparation, properties, and vibrational spectra of complexes containing the dicloro-, dibromo-, and diiodoaureate(I) ions. *J. Chem. Soc. Dalton Trans.* **1973**, 1845–1848.

[12] R. W. Buckley, P. C. Healy, W. A. Loughlin. Reduction of $[NBu_4][AuCl_4]$ to $[NBu_4][AuCl_2]$ with sodium acetylacetonate. *Aust. J. Chem.* **1997**, *50*, 775–778.

Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web site.