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The First Flights of a Molecular Shuttle Transporting Elements: Easy One-pot Formation of Organic Cyclic Arsanes, Stibanes and Bismutanes

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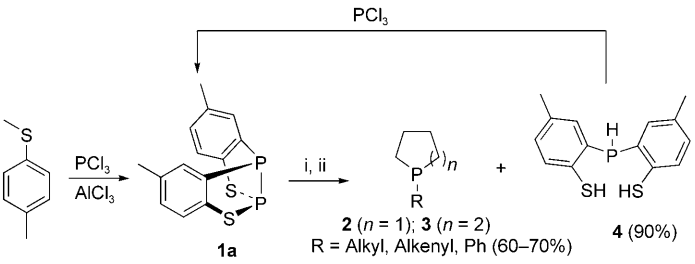
The increasing role of organic derivatives of arsenic, antimony, and bismuth in many fields of chemistry is due to their versatility as ligands,[1] their use in materials science[2] and their applications in the pharmacological field.[3] Despite this, few methods of synthesis of triorganoderivatives of these elements have been reported to date and they all involve multi-step procedures giving products in very low overall yields.[4] Moreover, the toxicity of these derivatives requires that their preparation must be carried out with strong attention and adequate precautions in their handling. For these reasons, to find synthetic one-pot procedures that permit the manipulation of these compounds to be minimised represents an interesting challenge.

Here we report a very simple synthesis of new arsenic-, antimony- and bismuth-donor reagents and their use in the one-pot synthesis of cyclic arsanes, stibanes and bismutanes, respectively, through a procedure in which the simultaneous formation of three C–As, C–Sb or C–Bi bonds is achieved.

Recently, we reported[5] (Scheme 1) a new synthesis of tertiary cyclic phosphanes **2** and **3** in 60–70% yields[5a,b] by addition of a bis(Grignard) reagent and a Grignard reagent to an unusual phosphorus-donor reagent, the benzothiadiphosphole **1a**,[6] called by us a "butterfly reagent"[7] owing to its particular folded structure. At the end of the reaction the starting reagent **1a** was quantitatively regenerated by addition of one equivalent amount of PCl_3 to the end-product **4**, which is the remainder of **1a** obtained after quenching the reaction mixture with water (Scheme 1). More recently, we found that tertiary phosphanes are formed spontaneously in the reaction mixture, and that the quantitative regeneration of the reagent **1a** can be accomplished by simple addition of one equivalent amount of PCl_3 to the crude reaction mixture.[8]



i: $BrMg(CH_2)_3(CH_2)_nMgBr + RMgBr$
ii: H_2O

Scheme 1. One-pot synthesis of tertiary phosphanes.

Taking these findings into consideration, together with the fact that as As, Sb and Bi, belong to the same group of P they could show similar behaviour, we decided to try a transport process for these elements, in order to find a new protocol for obtaining cyclic organoarsanes, organostibanes and organobismutanes, which, to date, have been synthesised with multi-step procedures and in very low overall yields.[9]

For this purpose, firstly we tried the synthesis of new heterocycles **1b–d** (Scheme 2), by reaction between compound **4** and $AsCl_3$, $SbCl_3$, and $BiCl_3$, respectively.[10] With this reaction benzothiaphospharsole (**1b**), benzothiaphosphastibole (**1c**), and benzothiaphosphabismole (**1d**; Scheme 2) were isolated in almost quantitative yields (95–98%) and characterised.

It is worth noting that mass spectra of **1a–d** showed the same peak ($m/z = 243$), originating by the loss from the molecular ion of the fragment PS, AsS, SbS and BiS, respectively. At the same time, the ^{31}P NMR spectra showed a regular decrease of the chemical shifts on going from **1b** ($\delta =$ 78.6 ppm) to **1c** ($\delta = 52.7$ ppm), to **1d** ($\delta = 35.0$ ppm) in $[D_8]$THF, as a result both of the decrease in electronegativi-

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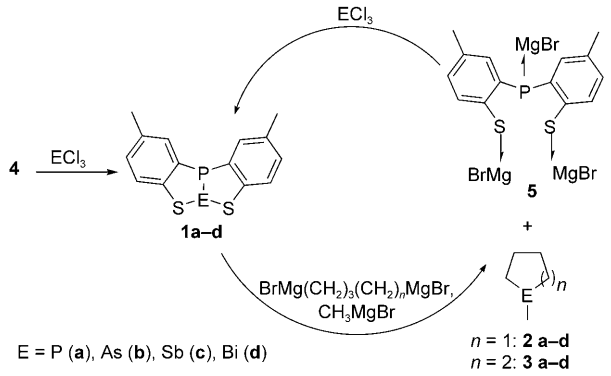


Scheme 2. Synthesis and reactions of element-donor reagents **1a–d**.

ty and of the concomitant increase in metallic character down to the group. Furthermore, we observed a decreasing solubility of these new heterocycles moving toward the heaviest elements that parallels the growing tendency to the self-assembling in dimeric or cluster-like structures.[11]

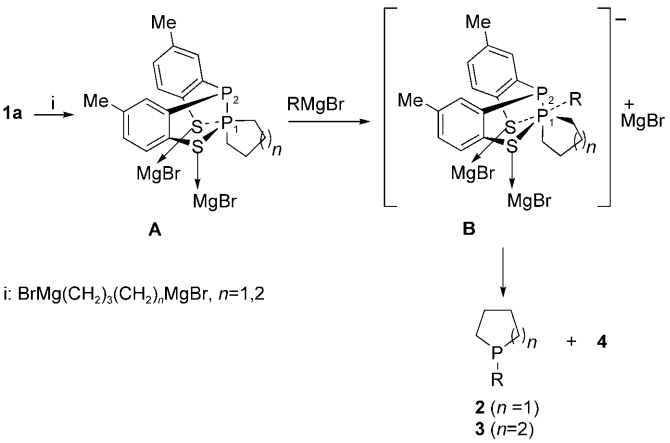
Once **1b–d** were obtained, we focused our efforts on their use as starting reagents to realise a one-pot synthesis of cyclic arsanes, stibanes and bismutanes. Taking in consideration that tertiary phosphanes are produced from **1a** directly in the reaction mixture,[8] we wanted to try to carry out a "catalytic process of transport of an element" aimed at the continuous formation of cyclic tertiary organoderivatives of P, As, Sb and Bi without isolation of any intermediate and with the "in situ" re-formation of starting "butterfly" reagents, as shown in Scheme 2. The "transporter system" is formed by two molecules. The first is the reagent **1**, which donates the atom that lies between the two sulfur atoms to Grignard reagents ($BrMg(CH_2)_3(CH_2)_nMgBr$ and CH_3MgBr) forming cyclic tertiary organoderivatives **2** or **3**. The second molecule, compound **5**—the magnesium salt precursor of **4**—obtained after spontaneous expulsion of the cyclic product as residue of the "butterfly reagent", can be easily re-transformed "in situ" into the starting reagent **1** by simple addition of ECl_3 (E = P, As, Sb, Bi). This double ability of compound **5**, either as acceptor of element when it reacts with ECl_3 and as donor of element in its "activate form" **1**, means that it can be considered as a catalytic carrier of the element, recovered at the end of the process.

With this method, we obtained compounds **2a–d** and **3a–d** in good to satisfactory yields. In particular, phosphanes were obtained in 70–80% yields, the new benzothiaphosphapharsole **1b** also acts as efficient arsenic-donor molecule, giving cyclic arsanes in 60–70% yields, while cyclic stibanes and bismutanes were obtained in 50–55 and 25–30% yields, respectively. This gradual decrease of the yields of cyclic products on going from starting reagent **1a** to **1d** could be explained by considering that the heavier elements Sb and Bi in Group 15 possess a reactivity different from that of the preceding elements, probably due to the formation of hypervalent species of Sb and Bi that make difficult the reaction with Grignard reagents (penta- and hexacoordinated species of bismuth have been often reported[12] to be very stable or substituted by ionic species).[1,13]

However, it has to be pointed out that our methodology allows us to obtain derivatives **2a–d** and **3a–d** in overall yields higher with respect to those reported so far, with a noticeable improvement in terms of safety of the whole process thanks to the possibility to carry out it in a one-pot process.

In addition, the yield of the re-formation of compound **1** from **5** is nearly quantitative, and the cycle can be repeated more times (i.e., after three cycles, **2a** was isolated in amount corresponding to a mean of 70% yields each cycle), thus avoiding the step-by-step separation of reaction products, which could imply a decrease of yields since compounds **1a–d** and **5** (as well as its neutral form **4**) are stable in solution but, once isolated, became air-sensitive and tend to form the corresponding oxides.

The efficiency of the one-pot one-step synthesis of cyclic derivatives of P, As, Sb and Bi can be explained by the intervention of penta- and hexacoordinated intermediates, such as **A** and **B** in Scheme 3, shown for the case of phosphorus derivatives as an example.



Scheme 3. Hypervalent phosphorus intermediates involved in the formation of tertiary cyclic phosphanes.

The formation of these species, detected by ^{31}P NMR spectroscopy in the case of formation of phosphanes,[5b,14] is highly favoured because the rigid "butterfly"[6] structure of **1a**, with its bicyclic condensed system around the phosphorus atom, strongly favours the formation of hypervalent intermediates,[15] each ring being a factor of great stability, reducing the overcrowding.

In summary, we have realised the synthesis of new heterocycles **1b–d** bearing P–As, P–Sb and P–Bi bonds that can act, in turn, as carriers of arsenic, antimony, and bismuth to give, in good yields, cyclic organoarsanes, organostibanes and organobismutanes. The starting phosphorus-, arsenic-, antimony- and bismuth-donor reagents can be re-formed in situ by simple addition to the crude reaction mixture of PCl_3, $AsCl_3$, $SbCl_3$ or $BiCl_3$, respectively, without isolation of

intermediates, thus permitting to consider the whole process as a catalytic cycle.

Experimental Section

Preparation of compounds 1b–d:[10] $AsCl_3$ (or $SbCl_3$, or $BiCl_3$, 1.0 mmol) was added, at room temperature, to a solution of compound **4** (0.278 g, 1.0 mmol) in dichloromethane (30 mL) under argon atmosphere. After about 20 m. the solvent was removed giving quantitatively the corresponding compound **1**.

Preparation of compound 5: A solution of a Grignard reagent (3.0 mmol) in THF was added, at 25 °C, to a solution of **1a** (1.0 mmol) in anhydrous THF (35 mL) under argon. The reaction was monitored by ^{31}P NMR spectrometry: when the signals of reagent **1a** disappeared, and those of the tertiary phosphane and of **5** appeared, the solvent was removed under vacuum to about 1/5 of the starting volume, and the resulting suspension was filtered under argon. The white salt **5** was washed once with anhydrous THF (1–2 mL) and the solvent was removed under argon atmosphere.

Preparation of compounds 2a–d and 3a–d: ECl_3 (2.0 mmol, E = P, As, Sb, Bi) was added to a suspension of **5** (2.0 mmol) in THF (20–30 mL). After about 20 min the formation of compound **1** (**1a**, **1b**, **1c** or **1d**) was complete. Then, a solution containing $BrMg(CH_2)_nMgBr$ ($n = 1$ or 2, 2.0 mmol) and CH_3MgBr (2.0 mmol) in THF was quickly added, at room temperature. The reaction course was monitored by GC-MS and ^{31}P NMR spectroscopy. After about 40 min. the signal of the starting reagent **1** disappeared, and concomitantly appeared those of **5** and **2** ($n = 1$, or **3**, $n = 2$). At this stage, an equivalent amount of ECl_3 was added to the crude reaction mixture and the re-formation of corresponding reagent **1** was detected. The cycle was repeated at least three times; at the end compound **5** was recovered by filtration, and cyclic compound was isolated from the solution by removal of the solvent followed by distillation. More details and other procedures are given in the Supporting Information, together with chemicophysical data of all synthesised compounds.

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