A Practical One-Pot Transformation of Triphenylphosphine Oxide to Triphenylphosphine by Reduction of in situ Generated Triphenylphosphine Dichloride

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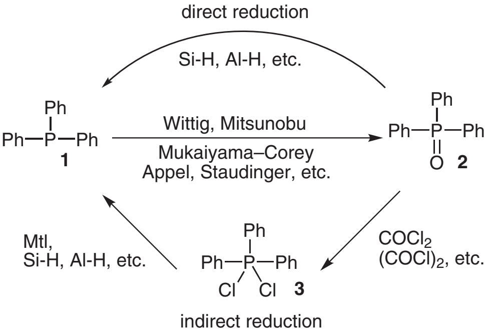
Abstract: One-pot transformation of triphenylphosphine oxide to triphenylphosphine was achieved by the reaction of triphenylphosphine oxide with oxalyl chloride, which led to the formation of triphenylphosphine dichloride, and subsequent reduction of triphenylphosphine dichloride with a combination of aluminum–catalytic metal salt.

Key words: triphenylphosphine, triphenylphosphine oxide, reduction, aluminum, multi redox system

Triphenylphosphine (**1**) is a versatile reagent and has been frequently used in various organic reactions, for example, Wittig reaction,[1] Mitsunobu reaction,[2] Mukaiyama–Corey lactonization,[3] Appel reaction,[4] and Staudinger reaction.[5] In these reactions, **1** is converted into triphenylphosphine oxide (**2**). Thus, a large amount of **2** is produced as waste material. Therefore, the development of a facile method for reducing **2** to **1** is desired to render these reactions environmentally benign and sustainable.

Direct reduction of **2** to **1** has been achieved successfully using various reductants including metal hydrides such as lithium aluminum hydride,[6] trichlorosilane,[7] and methylpolysiloxane,[8] low-valent metals such as magnesium/titanocene dichloride,[9] metal salts such as samarium iodide,[10] nonmetallic organic reagents such as hydrocarbon/activated carbon[11] and hexaethylphosphorus triamide/phosphorus oxytrichloride,[12] and electroreduction.[13] The reduction methods developed thus far are, however, not practical because they always require stoichiometric amounts of reducing agents that are expensive, explosive, and/or are not easy to handle.

As an alternative method, indirect reduction of **2** to **1** via triphenylphosphine dichloride **3** has also been examined (Scheme 1). Triphenylphosphine dichloride (**3**) has been prepared by the treatment of **2** with chlorination reagents such as phosphorus pentachloride,[6a] phosgene,[14] diphosgene,[15] triphosgene,[16] and oxalyl chloride.[17] Reduction of **3** to **1** has been carried out by the use of metallic reductants such as sodium[17] and metal hydrides such as $LiAlH_4$.[18] Again, these methods do not necessarily produce satisfactory results because they involve complicated procedures and special care should be taken especially when a large amount of **2** is treated.[19]



Scheme 1 Recycling use of triphenylphosphine

Aluminum is an ideal reducing agent because it is cheap, air- and moisture-stable, and environmentally benign. Aluminum releases three electrons per atom and acts as a powerful reductant (standard redox potential = –1.662 V). However, the use of aluminum in organic synthesis is rather limited because it is easily deactivated in air by forming a thin oxide layer on its surface. Hermeling carried out the reduction of **3** to **1** by using a fine aluminum powder (0.1–2 mm Ø).[20] A fine aluminum powder is essential for the efficient reduction of **3**; however, the aluminum powder thus formed is explosive and special care is required.

We have developed chemical transformations promoted by a combination of aluminum and a catalytic metal salt, wherein aluminum acts as an electron pool and the catalytic amount of metal salt acts as a mediator for electron transfer from aluminum to substrates.[21] Indeed, various combinations of aluminum and metal salts such as lead(II) bromide, nickel(II) chloride, and chromium(III) chloride have been developed to promote carbon–carbon bond formation as well as highly selective functionalization. These reactions have been successfully employed for the synthesis of useful compounds such as β-lactam antibiotics and β-lactamase inhibitors.

In this communication, we describe the one-pot reduction of **2** to **1** by the chlorination of **2** to **3** with oxalyl chloride and the subsequent reduction of **3** generated in situ using an aluminum/metal salt redox system, thereby offering a facile and simple recycling system of triphenylphosphine (**1**).

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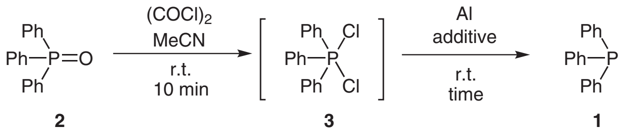
A typical reaction procedure is described as follows (Table 1, entry 1). To a mixture of **2** (1.4 g, 5.0 mmol), finely cut aluminum foil (137 mg, 5.0 mmol, ca. 1×1×0.012 mm^3), and acetonitrile (5 mL) was added oxalyl chloride (0.46 mL, 5.1 mmol) dropwise at room temperature under argon atmosphere. The resulting mixture was stirred for 10 minutes at room temperature. ^{31}P NMR analysis of the aliquot of the mixture revealed that chlorination of **2** proceeded smoothly to give **3** (δ = 50.1 ppm) quantitatively. To the resulting mixture was added lead(II) bromide (19.9 mg, 0.05 mmol) in one portion, and the mixture was stirred for 6 minutes at ambient temperature to give **1** (1276 mg, 4.9 mmol, 93%).[22]

Table 1 One-Pot Reduction of **2** to **1** via **3** by Using Aluminum–Catalytic Metal-Salt Redox System[a]



Entry	Additive	mol%	Time	Yield (%)[b] of **1**	Yield (%)[b] of **2**
1	$PbBr_2$	1	6 min	93	4
2	none	0	24 h	7	82
3	$SnCl_2$	2	1 h	97	2
4	$BiCl_3$	1	1 h	67	31
5	$FeCl_3$	2 (5)[d]	1 h	ND (46)[d]	94 (42)[d]
6	$ZnCl_2$[c]	2 (25)[d]	1 h	ND (53)[d]	93 (43)[d]
7	$NiCl_2$	1	1 h	ND	97

[a] Conditions: **2** (5 mmol), $(COCl)_2$ (100 mol%), finely cut aluminum foils (400 mol%), additive, MeCN (5 mL), r.t.
[b] Yields of isolated compounds.
[c] Anhydrous.
[d] After 24 h.

The metal salts showed considerable effects on the reaction (Table 1). In the absence of lead(II) bromide, the reduction reaction hardly proceeded and only 7% of **1** was obtained even after 24 hours (entry 2). Tin(II) chloride and bismuth(III) chloride also effectively promoted the reduction reaction, affording **1** in 97% and 67% yields, respectively (entries 3 and 4). The reduction did not proceed efficiently when iron(III) chloride, zinc(II) chloride, and nickel(II) chloride were used (entries 5–7). Thus, **1** was not detected and most of **2** (93–97%) was recovered after 1 hour, while 50% of **1** was obtained after 24 hours.

The proper choice of solvents was also important (Table 2). Among the solvents examined, acetonitrile was the best solvent to give **1** quantitatively (entry 1), whereas 1,2-dimethoxyethane (DME), chloroform ($CHCl_3$), and chlorobenzene (PhCl) gave **1** in moderate yields (79–57%, entries 2–4). The reduction reaction hardly proceeded in the presence of 2-butanone (MeCOEt) and *N*,*N*-dimethylformamide (DMF, entries 5 and 6).

Table 2 Effect of Solvent on Al/$PbBr_2$ System[a]

Entry	Solvent	Yield of **1** (%)[b]
1	MeCN	95
2	DME	79
3	$CHCl_3$	78
4	PhCl	57
5	MeCOEt	7
6	DMF	1

[a] Conditions: **2** (5 mmol), $(COCl)_2$ (100 mol%), finely cut aluminum foil (400 mol%), $PbBr_2$ (1 mol%), MeCN (5 mL), r.t., 0.1 h.
[b] Yields of isolated **1**.

The reduction reaction was carried out using different shapes of commercially available aluminum specimens such as an aluminum foil, powder, a plate, and pellets (Table 3). As the finely cut aluminum foil (1×1×0.012 mm^3, entry 1) and aluminum powder (200 mesh, entry 2) had a large surface area, reduction from **3** to **1** was completed using only 1 molar equivalent of aluminum. On the other hand, the reduction did not proceed efficiently by using aluminum plate and pellets because their surface area was considerably small: indeed, a grain of an aluminum pellet (4 mmØ×6 mm, ca. 200 mg, 7.4 mmol) gave **1** in 49% yield after 1 hour (entry 4). The yield of **1** increased by using a large excess amount of aluminum plate and pellets: an aluminum plate (30×5×0.5 mm^3, entry 3) and pellets (4 mmØ×6 mm, 79 mmol, 16 mol equiv, entry 5) gave **1** in 94% and 96% yields, respectively, within 6 minutes.

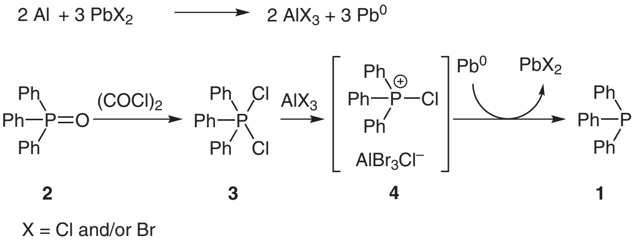
Table 3 Shape of Al Specimen and Recycle Use of Al Pellets[a]

Entry	Al	mmol	$PbBr_2$ (mol%)	Yield **1** (%)[b]
1	finely cut foil (1 × 1 × 0.012 mm^3)	5	1	95
2	powder (200 mesh)	5	1	88
3	plate (30 × 5 × 0.5 mm^3)	75	1	94
4	pellet (3–5 mm Ø)[c]	5	1	49
5	pellet (3–5 mm Ø)[d]	79	1	96
6	pellet (3–5 mm Ø)[e,f]	76	0	93
7	pellet (3–5 mm Ø)[e,g]	72	0	92

[a] Conditions: **2** (5 mmol), $(COCl)_2$ (100 mol%), MeCN (5 mL), r.t., 6 min.
[b] Yields of isolated **1**.
[c] 1 h.
[d] 1st run.
[e] In absence of additional $PbBr_2$.
[f] 2nd run.
[g] 3rd run.

It is interesting to note that after the reaction (entry 5), excess aluminum pellets were recovered easily by filtration and they could be used repeatedly without adding lead(II) bromide (entries 6 and 7). Thus, chlorination–reduction (vide supra) of **2** (5 mmol) with aluminum pellets (79 mmol) in the presence of lead(II) bromide (0.5 mmol) gave **1** in 96% yield (first run) with recovered aluminum pellets (76 mmol). The recovered aluminum pellets were used again for the second run. It is notable that the second run proceeded smoothly in the absence of lead(II) bromide to give **1** in 93% yield, and 72 mmol of aluminum pellets was recovered (entry 6). The third run with the recovered aluminum pellets afforded **1** in 92% yield (third run, entry 7). In all the cases, **2** was recovered in less than 2% yield.

A plausible reaction mechanism is explained as follows (Scheme 2). As confirmed by ^{31}P NMR, **2** was firstly converted into **3** by the treatment with oxalyl chloride. Thus, the in situ generated **3** was reduced with aluminum/catalytic lead bromide to give **1**. Reduction of **3** to **1** was a two-electron process, whereas aluminum atom releases three electrons to form an aluminum ion (Al^{3+}). Theoretically, 0.67 mmol of aluminum is consumed in the reductive dechlorination of 1 mmol of **3**. In fact, approximately 0.6–0.8 mmol of aluminum were consumed in the reduction of 1 mmol of **3**, indicating that the electron transfer from aluminum to **3** proceeded efficiently. In the aluminum/catalytic lead bromide redox system, a redox reaction occurred between aluminum and lead bromide to generate low-valent lead (Pb^0) and aluminum bromide. Aluminum bromide acted as a Lewis acid on **3** to produce active tetravalent phosphonium species **4**. The in situ generated Pb^0 reduced **4** to afford **1** and lead dihalide (PbX_2). Thus generated PbX_2 was reduced with aluminum to give Pb^0 and aluminum salt (AlX_3) again.



Scheme 2 A plausible mechanism

The surface of aluminum was activated by the treatment of lead bromide. The activated aluminum surface also acted as a reducing reagent for the dechlorination of **4**. Indeed, the aluminum pellets recovered in the previous run promoted the reductive dechlorination of **3** without further addition of lead bromide.

The treatment of triphenylphosphine oxide with oxalyl chloride immediately gave triphenylphosphine dichloride. A combination of aluminum and a catalytic amount of metal salt reduced triphenylphosphine dichloride to triphenylphosphine quantitatively under mild conditions. Aluminum was activated by the metal salt, and the activated aluminum was recovered and used repeatedly without further activation. This indirect reduction offers an efficient regeneration system of triphenylphosphine.

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