Photochemical transformation of chlorobenzenes and white phosphorus into arylphosphines and phosphonium salts†

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Chlorobenzenes are important starting materials for the preparation of commercially valuable triarylphosphines and tetraarylphosphonium salts, but their use for the direct arylation of elemental phosphorus has been elusive. Here we describe a simple photochemical route toward such products. UV-LED irradiation (365 nm) of chlorobenzenes, white phosphorus (P4) and the organic super-photoreductant tetrakis(dimethylamino)ethylene (TDAE) affords the desired arylphosphorus compounds in a single reaction step.

Commercially valuable and academically interesting organophosphorus compounds (OPCs) such as arylated phosphines (Ar3P) and phosphonium salts ([Ar4P]+) are currently prepared by a wasteful and inefficient multi-step procedure which relies on the initial oxidation of white phosphorus (P4) using toxic Cl2 gas to give highly reactive PCl3 which is further converted into the desired monophosphorus species (Fig. 1a).1,2 Given the numerous drawbacks of this method the direct transformation of P4 into OPCs and other P-containing compounds, avoiding potentially hazardous intermediates, has long been an exceedingly important yet challenging objective.3

Pioneering studies by Barton and co-workers demonstrated the excellent ability of P4 to trap carbon-centered radicals, and that this can provide the basis for subsequent transformation of white phosphorus into valuable OPCs.4,5 Subsequently, stoichiometric functionalization reactions were reported by Cummins and co-workers in which the generation of reactive organoradicals by reacting organic bromides and iodides with a titanium(III) complex (or more recently samarium(II) halides) is again the fundamental first step in converting P4 into the corresponding tertiary phosphines (Fig. 1b).6,7 Expanding on these stoichiometric methodologies in which organic halides are reduced by metal-containing reductants in the presence of P4, recently, we reported the first catalytic procedure to obtain OPCs directly from P4 (Fig. 1c).8–10 The reduced form of a photoexcited iridium photocatalyst or, alternatively, an organo-photocatalyst is able to reduce aryl iodides (ArI) to generate carbon-centered aryl radicals which are again trapped by P4 to directly form arylated phosphines and phosphonium salts.

All these efforts to prepare OPCs directly from P4 through the use of carbon-centered radicals were realized only by using...
organic bromides and iodides.\textsuperscript{11--13} However, from an economic point of view the use of bromo- and iodobenzenes for the preparation of tertiary phosphines is infeasible, with these substrates often even being more expensive than the target phosphines. In contrast, organic chlorides are cheap and abundant substrates which comprise over two-thirds of commercially available aryl halides,\textsuperscript{14,15} but their use as substrates and radical precursors in photocatalysis and photochemistry is challenging because of their chemical inertness.\textsuperscript{16--19} Herein, we describe a simple photochemical method for the preparation of various valuable triarylphosphines and tetraarylphosphonium salts directly from P$_4$ by using only readily and cheaply commercially available aryl chlorides. For the transformation of one P$_4$ molecule into four [Ph$_4$P]Cl at least 16 PhCl have to be reduced to form the needed 16 P–C bonds. For a clean stoichiometric functionalization, a stoichiometric ratio of TDAE to PhCl of 8 : 16 (equiv. based on P$_4$) should suffice to efficiently generate the final phosphonium salt (assuming TDAE acts as a two-electron donor; \textit{vide infra}). Nevertheless, adapting the reaction stoichiometry to this level was found to result in appreciably reduced conversion (see ESI,† S3 and Table S5). In part this is likely due to side reactions such as forming benzene from an aryl radical/anion or generating biphenyl by recombination of two radicals (confirmed by GC-MS). Although all P$_4$ is consumed quantitative product formation is not observed, even after an increase of the reaction time (40 h) as shown by quantitative $^{31}$P($^1$H) NMR spectroscopy (see ESI,† S3 and Table S6). The loss of phosphorus intensity is possibly caused by formation of polymerized phosphorus species, which was also a limiting factor in our recently reported photocatalytic procedure.\textsuperscript{8}

Control experiments confirmed that all reaction components (P$_4$, PhCl, TDAE and UV light) are necessary to observe product formation (Table 1, entries 2–4). Switching from PhCl to the less reactive PhF or the more easily reducible substrates PhBr or PhI was found to be detrimental (Table 1, entries 5–7). In the case of PhF no reaction occurred at all. Also, replacing P$_4$ with red phosphorus yielded no product (Table 1, entry 8).

Various other substituted aryl chlorides could also successfully be employed under identical reaction conditions, albeit with somewhat lower conversions than for chlorobenzene (see ESI,† Table S8 and Fig. S22). The investigated substrate scope shows that the method is more suitable for substrates bearing electron-donating (Me, OMe) groups than for chloroarenes with electron-withdrawing groups (EWGs, such as CF$_3$, COOME), which generally gave poor conversions. Gratifyingly, not only aryl radicals led to product formation. For benzyl chloride 27% conversion to tribenzylphosphine was achieved. Even more impressively, employing (2-chloroethyl)benzene as substrate the product tris(2-phenylethyl)phosphine was formed selectively in 75% NMR yield. Selected products (tetraphenyolphosphonium chloride and tris(2-phenylethyl)phosphine) were synthesized by performing reactions on a preparative scale and isolated in modest yields by precipitation from dichloromethane/hexane (for the phosphonium salt) or fractional distillation (for the phosphine). See the ESI† for details of the purification and isolation of these products.

The chemical inertness of these chlorobenzenes (e.g. PhCl; $-2.78$ V vs. SCE in DMF,$^{21}$ Fig. 2) is due to the high energetic barrier for C–Cl bond activation. To overcome this a strong (photo)reductant is needed. TDAE as a single-electron reducing agent with an oxidation potential of $-0.78$ V vs. SCE (CH$_3$CN)$^{22}$ is not strong enough to split off a chloride anion to generate aryl radicals. By contrast the photoactive excited state of TDAE (TDAE) offers an extraordinary reducing power of $-3.4$ V vs. SCE\textsuperscript{20} (Fig. 2) which makes it a super-photoelectroreductant. Luminescence lifetime measurements showed that the excited state of TDAE is quenched by acetone.$^{20}$ Thus, instead of a direct single electron transfer (SET) from photoexcited TDAE to the substrate, acetone ($-2.84$ V vs. SCE)$^{23}$ is reduced and forms an aceton radical anion which subsequently undergoes SET to the organic chlorides and generates carbon-centered radicals. Using a solvent which cannot be reduced by photoexcited TDAE such as acetonitrile or benzene ($-3.42$ V vs. SCE)$^{24}$ or

![Table 1](image)
employing the substrate PhCl as solvent decreased the yield of phosphonium salt and phosphine (see ESI, † S3, Table S4).

Usually, organic chlorides are more inactive substrates than the corresponding bromides and iodides because of their high bond dissociation energy (PhCl 327 kJ mol$^{-1}$). As mentioned above, however, using substrates such as bromobenzene or iodobenzene (PhBr $-$2.44 V vs. SCE, PhI $-$1.93 V vs. SCE) for this photochemical procedure reduced the product formation. While the reasons for this are not entirely clear, it is presumably related to the fact that the bromide and iodide can more easily be reduced than aryl chlorides, leading to more rapid accumulation of aryl radicals, that may then be more prone to unwanted side-reactions such as dimerization or over-reduction (+0.05 V vs. SCE). In contrast, using aryl fluorides as radical source yielded no product at all, presumably because PhF is outcompeted by the solvent as an oxidative quencher of radicals thus generated then sequentially functionalize P$_4$ by donor. Nevertheless, mechanistic investigations and in situ NMR experiments (see ESI, † S6) using deuterated acetone-d$_6$ showed clear deuterium incorporation into these intermediates, suggesting that acetone is involved in the mechanism. It should be noted, however, that P$_4$ arylation also proceeds in the absence of acetone with 30–40% total conversion to a mixture of P$_3$Cl$_2$ and P$_3$P$^{31P}$ NMR spectroscopic monitoring, see the ESI, † S6 and Table S3). For the formation of the intermediates PhPH$_2$ and P$_2$PH$_2$, the diphosphine (P$_2$P$_2$), Ph$_3$P and finally [Ph$_4$P]Cl. The first arylation step to the primary phosphine (PhPH$_2$) is presumably too rapid to be tracked by $^{31P}$NMR, but small amounts of Ph$_3$P were observable during NMR monitoring (ESI, † S6.1 and Fig. S32). For the formation of the intermediates PhPH$_2$ and P$_2$PH the required H-atoms could potentially be transferred from the oxidized radical cation TDAE$^{+*}$ (see Fig. 4) which is an effective H-atom donor. Nevertheless, mechanistic investigations and in situ NMR experiments (see ESI, † S6) showed clear deuteration incorporation into these intermediates, suggesting that acetone is involved in the mechanism. It should be noted, however, that P$_4$ arylation also proceeds in the absence of acetone with 30–40% total conversion to a mixture of P$_3$Cl$_2$ and P$_3$P$^{31P}$ NMR spectroscopic monitoring, see the ESI, † Table S4). Hence, the direct, non-acetone mediated reduction may be an additional, significant pathway.

To validate their intermediacy, the photochemical phenylation was also analyzed starting from the different arylated
phosphorus compounds PhPH₂, Ph₂PH, Ph₃P and Ph₄P (see ESI,† S7). By using Ph₃P as a starting material a mixture of [Ph₃P]Cl (76%) and Ph₃P (15%) could be obtained in good yields. PhPH₂ also showed good conversion to the phosphonium salt (68%) and using Ph₃P₂ as the P-containing species yielded a mixture of 55% [Ph₃P]Cl and 28% Ph₃P. Interestingly, further investigations of the stability of the phosphonium salt under the applied photochemical conditions confirmed some decomposition of the product (loss of [Ph₃P]Cl intensity dependent on amount of TDAE, see ESI,† S7 and Table S13) which is probably a factor behind the consistently subquantitative yields of the P₄ arylation reaction.

Finally, it was noted that during the photochemical reaction [TDAE]Cl₃ is formed as a side product (see ESI,† S8) which is almost completely insoluble in acetone and precipitates as a white solid over the course of the reaction and can be recovered by simple filtration. Since it is known that [TDAE]Cl₂ can be used to regenerate TDAE using simple reductants such as Zn,14 this recovery suggests the possibility of using the organic photoreductant as part of a closed loop, in which a much cheaper reagent acts as the effective terminal reductant. Synthetic efforts in this direction are currently underway.

In conclusion, we have described herein the direct photochemical arylation of white phosphorus using inexpensive, commercially available aryl chlorides for the first time, which has long been an important yet challenging objective. The simple light-driven procedure is mediated by TDAE and acetone under irradiation with UV light. The remarkable reducing power of photoexcited TDAE enables the reduction of different substituted organic chlorides to generate the corresponding aryl radicals which can be trapped by P₄ to form new P–C bonds and ultimately valuable aryl phosphines and phosphonium salts. While these observations represent an important proof-of-principle, the present method still suffers from several practical disadvantages, e.g. the need for an excess of aryl chloride and TDAE, poor selectivities toward the formation of either phosphonium salt or phosphine and our current inability to recycle the TDAE photoreductant effectively. Solutions to these limitations are the subject of ongoing investigations, alongside further studies into the activation of chloro- and bromobenzenes for (catalytic) P₄ functionalization.

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Conflicts of interest
There are no conflicts to declare.

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