



Photocatalytic stannylation of white phosphorus†

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Organophosphorus compounds (OPCs) are highly important chemicals, finding numerous applications in both academia and industry. Herein we describe a simple photocatalytic method for the stannylation of white phosphorus (P₄) using a cheap, commercially-available distannane, (Bu₃Sn)₂, and anthraquinone as a simple photocatalyst. Subsequent 'one pot' transformation of the resulting stannylated monophosphine intermediate (Bu₃Sn)₃P provides direct, convenient and versatile access to valuable OPCs such as acylated phosphines and tetraalkylphosphonium salts.

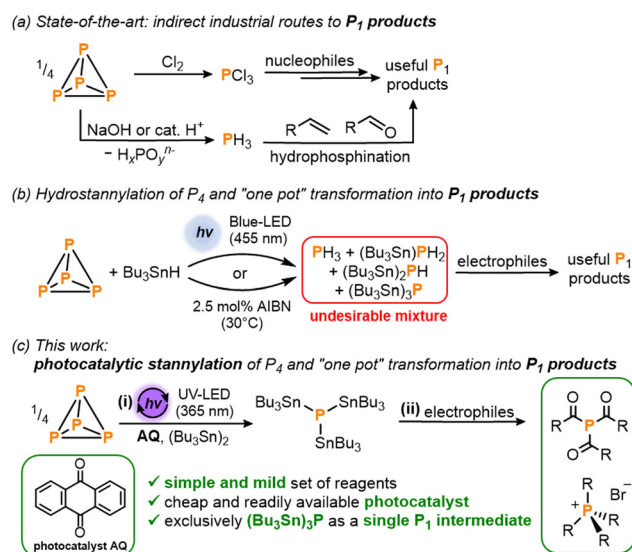
White phosphorus (P₄) – the most chemically important allotrope of this ubiquitous and abundant element – acts as the common precursor from which all commercially valuable and academically important organophosphorus compounds (OPCs) are prepared. The current methods used for the industrial synthesis of these myriad useful P₁ products include the oxidation of P₄ with toxic Cl₂ gas to generate PCl₃ which can subsequently be transformed into a variety of OPCs by reaction with nucleophiles (Scheme 1a). As an alternative route, initial acid- or base-mediated disproportionation of P₄ can be used to generate highly toxic PH₃ gas which is then employed for the hydrophosphination of unsaturated organic substrates.¹

Given the drawbacks of these methods, a highly prominent aim has long been to find ways of bypassing these multi-step procedures. In particular, there is a longstanding desire to develop more step-efficient *direct* – and, ideally, *catalytic* – methods to functionalize P₄ and generate OPCs in a single reaction.

As a result, for several decades comprehensive efforts have been made to better understand the fundamental reactivity of P₄.² However, it is only very recently that it has finally become

possible to successfully transform P₄ directly into a variety of useful P₁ products.³ Moreover, and despite these extensive investigations, the number of successful examples remains extremely low, and those that do exist still suffer from substantial limitations.⁴ As such, there remains a clear need to expand the range of strategies available for direct, productive P₄ activation, with new catalytic methods being particularly desirable.^{4a}

In one of our own contributions to this area, we recently reported a simple 'one pot' method in which the classical radical reagent tri-*n*-butyltin hydride (Bu₃SnH) is used for initial hydrostannylation of



Scheme 1 (a) Current state-of-the-art industrial methods for the synthesis of valuable P₁ products.¹ (b) Recently reported hydrostannylation of white phosphorus (P₄) using Bu₃SnH followed by reaction with electrophiles to generate useful P₁ products in a 'one-pot' fashion.⁵ (c) This work: (i) photocatalytic stannylation of P₄ using the photocatalyst anthraquinone (AQ) and hexabutylstannane (Bu₃Sn)₂; and (ii) subsequent functionalization of the intermediate (Bu₃Sn)₃P with electrophiles into products such as triacylphosphines and tetraalkylphosphonium salts.

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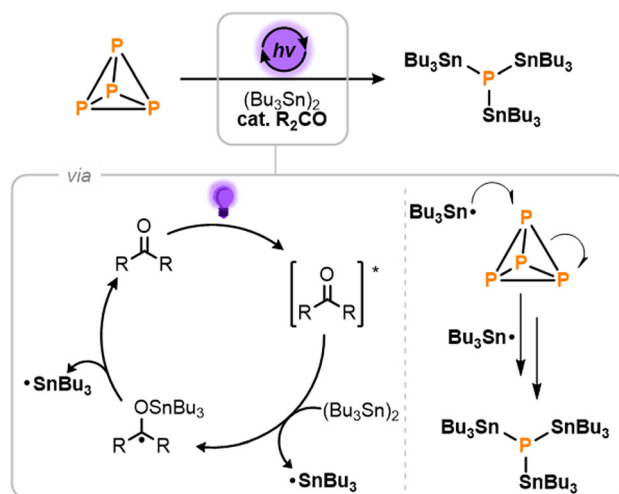
P_4 (Scheme 1b).⁵ This reductive P_4 activation is mediated either by light or by a chemical radical initiator such as AIBN (azobis(isobutyronitrile)) which can initiate a radical chain reaction that breaks down the P_4 tetrahedron, yielding a mixture of hydrostannylated phosphines $(Bu_3Sn)_xPH_{3-x}$ ($x = 0-3$). Key to this mechanism is the attack of stannyl radicals ($Bu_3Sn^\bullet$) on the P-P bonds of P_4 . The resulting $(Bu_3Sn)_xPH_{3-x}$ mixture can then be converted into a number of important and useful OPCs by reaction with electrophiles.⁵

Unfortunately, one significant disadvantage of this hydrostannylation strategy is the complexity of the $(Bu_3Sn)_xPH_{3-x}$ mixture, which complicates 'downstream' reaction development by requiring functionalization of two different types of bond (P-Sn and P-H), both of which are distributed over four distinct molecules. Moreover, the presence of gaseous PH_3 as a component of this mixture has been suggested to have a limiting effect on overall yields as it can easily be lost during subsequent manipulations,^{4a} and it is also problematic from a safety perspective.

These drawbacks would be overcome if the initial P_4 reduction step could instead furnish a single species with just one functionalizable motif, but with reactivity otherwise similar to $(Bu_3Sn)_xPH_{3-x}$. To achieve this, we describe herein a simple photocatalytic strategy for the atom-precise stannylation of P_4 using the cheap, commercially-available distannane $(Bu_3Sn)_2$ and simple benzophenone derivatives as photocatalysts (Scheme 1c). This new procedure generates exclusively the stannylated monophosphine $(Bu_3Sn)_3P$ and subsequent, simplified 'one pot' transformations with electrophiles afford valuable OPCs including acylated phosphines and alkylated phosphonium salts.

Based on the analysis above, we sought to develop a new method by which P_4 could be selectively transformed into $(Bu_3Sn)_3P$ as the sole product.⁶ It is worth noting that the closely related product $(Ph_3Sn)_3P$ has previously been prepared from P_4 using Ph_3SnCl as the stannylating reagent, but this required use of a relatively elaborate Ti(III) reagent as a halogen atom abstractor.^{3f} Instead, we imagined that an ideal reagent for such a reaction would be the distannane $(Bu_3Sn)_2$, which is cheap to purchase and could in principle provide the target phosphine with perfect atom economy.⁷ Indeed, Sn-Sn homolysis of $(Bu_3Sn)_2$ is known to furnish $Bu_3Sn^\bullet$ radicals, which previous work has shown are capable of adding to P_4 .^{3f,5} However, achieving this homolysis directly requires extreme temperatures or very high energy UV light irradiation that is known to lead to unselective reactivity, and is also unlikely to be compatible with P_4 .⁸⁻¹⁰ Fortunately, it has been reported that simple ketones can be used as photocatalysts to access $Bu_3Sn^\bullet$ radicals by Sn-Sn bond cleavage under much lower energy irradiation.¹¹

The light-driven photocatalytic stannylation of P_4 was therefore targeted, based on the mechanistic proposal outlined in Scheme 2.⁹ It was anticipated that photoirradiation of the ketone R_2CO would first provide an excited state, $[R_2CO]^*$,¹² capable of reacting with $(Bu_3Sn)_2$ to generate a stannylated ketyl radical and a free $Bu_3Sn^\bullet$ radical.¹¹ The former could then



Scheme 2 Proposed mechanism for the light-driven, photocatalytic stannylation of P_4 in the presence of hexabutyldistannane, $(Bu_3Sn)_2$, and a ketone photocatalyst, R_2CO .

thermally release a second $Bu_3Sn^\bullet$ radical to close the catalytic cycle. Once formed, these $Bu_3Sn^\bullet$ radicals would then add to the P-P bonds of P_4 , ultimately breaking it down to generate $(Bu_3Sn)_3P$ as the only P_1 product.¹³

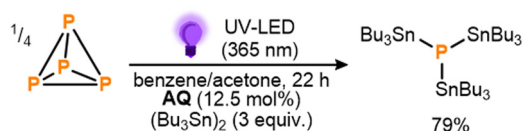
To begin, benzophenone (**BP**) was chosen as a proof-of-principle photocatalyst due to both its simplicity and the fact that its photoreactivity towards hexaalkyldistannanes has been studied previously.^{11d} Gratifyingly, after an initial optimization the photocatalytic stannylation of P_4 could successfully be achieved, with use of 25 mol% **BP** (all stoichiometries, in both equiv. and mol%, are defined per P atom) and a 3.3-fold excess (5 equiv.) of $(Bu_3Sn)_2$ providing 50% conversion to the target stannylated phosphine $(Bu_3Sn)_3P$ after stirring under near UV LEDs overnight (Scheme 3; see also ESI,† S3). Control experiments confirmed that all reaction components (P_4 , $(Bu_3Sn)_2$, **BP**, irradiation) were necessary for the reaction to proceed productively (see ESI,† S3, Table S1).

These initial results provided a clear proof-of-principle for the proposed mechanistic strategy. Notably, the observed conversion indicates the activation of at least three Sn-Sn bonds per available equivalent of **BP**,¹⁴ making this a rare example of a system where P_4 activation has been achieved catalytically, using an otherwise inert substrate.^{5,9a,9b,9e,15} Nevertheless, in order to improve the reaction outcome further, a broader range of benzophenone derivatives was subsequently screened, with several found to provide markedly improved performance (see ESI,† S5). Particularly impressive results were achieved using



Scheme 3 Initial conditions for the direct, photocatalytic stannylation of P_4 into $(Bu_3Sn)_3P$ optimized using benzophenone (**BP**) as photocatalyst. Stoichiometries in equiv. and mol% are defined per P atom.





Scheme 4 Optimized conditions for the direct, photocatalytic stannylation of P_4 into $(Bu_3Sn)_3P$ using anthraquinone (AQ) as photocatalyst. Stoichiometries in equiv. and mol% are defined per P atom.

anthraquinone (AQ) and following brief further optimization (see ESI,† S5 and S7) 79% conversion to $(Bu_3Sn)_3P$ could be achieved using significantly reduced loadings of both AQ (12.5 mol%) and $(Bu_3Sn)_2$ (3 equiv.) over the same timeframe (Scheme 4; see also ESI,† S7). Based on the catalytic cycle proposed in Scheme 2, this would correspond to a turnover number (TON) of 10.0 for AQ. Further reductions in catalyst loading to 6.3 mol% or 2.5 mol% were found to lead to even higher TONs (16.8 and 28.2, respectively), albeit at the cost of lower overall conversions (see ESI,† S7, Table S11).

With the stannylation of P_4 optimized, attention was then shifted to its subsequent, 'one pot' transformation into other useful P_1 products. Having previously developed procedures for the analogous transformation of the phosphine mixture $(Bu_3Sn)_xPH_{3-x}$, which includes $(Bu_3Sn)_3P$ as a minor component, it was anticipated that addition of electrophiles to photocatalytically-generated $(Bu_3Sn)_3P$ should be similarly productive,^{4,5} especially since neither the AQ photocatalyst nor the $(Bu_3Sn)_2$ starting material is expected to show appreciable reactivity towards such substrates. And, indeed, *in situ* addition of a variety of acid chlorides yielded the corresponding triacylphosphines $(R(O)C)_3P$ ($R = Ph, Cy, Ad, tBu, iPr, nBu, Me$) with good conversions of up to 75% (Scheme 5a(i)).^{5,16} Notably, and in comparison to our previously-reported hydrostannylation system, no exclusion of light and no additional base were required for this step, highlighting both the robustness and simplicity of $(Bu_3Sn)_3P$ as a " P^3- " synthon, relative to $(Bu_3Sn)_xPH_{3-x}$.

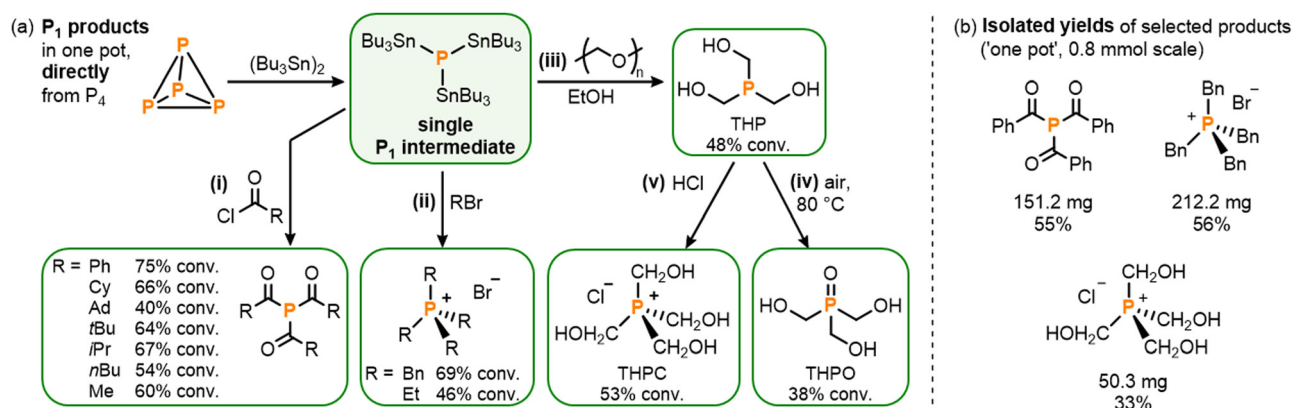
Similarly, reaction of $(Bu_3Sn)_3P$ with alkyl bromides RBr ($R = Bn, Et$) under moderate heating successfully provided

'one pot' access to the corresponding phosphonium salts, $[R_4P]Br$, including tetrabenzylphosphonium bromide, $[Bn_4P]Br$, which is a known precursor for useful Wittig chemistry (Scheme 5a(ii)).¹⁷ Again, no auxiliary base was required for these reactions, in contrast to the analogous procedures *via* $(Bu_3Sn)_xPH_{3-x}$ where the absence of base leads to a 50% reduction in yield.⁵

Finally, another industrially important class of P_1 products was targeted. Hydroxymethyl-substituted phosphine derivatives are used as flame-retardant materials (among a number of other applications),¹⁸ and could be accessed by reacting the stannylated monophosphine $(Bu_3Sn)_3P$ with paraformaldehyde in EtOH to furnish tris(hydroxymethyl)phosphine, THP ($HOCH_2)_3P$ (THP; Scheme 5a(iii)).^{18a} Subsequent exposure to air then yielded the corresponding phosphine oxide, $(HOCH_2)_3PO$ (THPO; Scheme 5a(iv)),^{18b} while the phosphonium salt tetrakis(hydroxymethyl)phosphonium chloride, $[(HOCH_2)_4P]Cl$ (THPC),^{18c,18d} could be accessed by quenching the *in situ* generated THP with HCl, all in one pot (Scheme 5a(v)).

To demonstrate the viability of these reactions on a preparative scale the triacylphosphine $(Ph(O)C)_3P$ and the phosphonium salts $[Bn_4P]Br$ and THPC were selected as representative examples for isolation (Scheme 5b; see ESI† S9). At 0.8 mmol scale $(PhC(O))_3P$ could be isolated in 55% yield,¹⁹ which compares well with our previously-reported hydrostannylation method (51%). $[Bn_4P]Br$ could also be isolated in good 56% yield, and THPC in a more modest yield of 33%.¹⁹

For this last reaction, efforts were also made to recover the Sn-containing compounds present at the end of the reaction. We have previously shown that for the analogous synthesis of THPC *via* $(Bu_3Sn)_xPH_{3-x}$ recovery of the Bu_3SnCl byproduct allows for convenient regeneration and recycling of the Bu_3SnH starting material, thus minimizing the formation of organotin-containing waste. Bu_3SnCl can also be used to regenerate $(Bu_3Sn)_2$ through a net one-electron reduction,⁸ meaning similar recycling should be feasible for this newer system, provided Bu_3SnCl can again be cleanly recovered. Satisfyingly, Bu_3SnCl could indeed be recovered during THPC workup through simple washing with diethyl



Scheme 5 (a) One-pot synthesis directly from P_4 , via photocatalytically generated P_1 intermediate $(Bu_3Sn)_3P$, of (i) triacylphosphines $(R(O)C)_3P$ (4 equiv. $RC(O)Cl$, $R = tBu, Ph, Me, nBu, Cy, iPr, Ad$), (ii) phosphonium salts $[R_4P]Br$ (5 equiv. RBr , $R = Bn, Et$, 60–80 °C), (iii) tris(hydroxymethyl)phosphine, THP (EtOH, 3 equiv. paraformaldehyde), (iv) tris(hydroxymethyl)phosphine oxide, THPO (as for (iii) then air, 80 °C), and (v) tetrakis(hydroxymethyl)phosphonium chloride, THPC (as for (iii) using 12.5 equiv. paraformaldehyde, then 10 equiv. HCl); and (b) Isolated yields for reactions on preparative scale (0.8 mmol). Stoichiometries in equiv. are defined per P atom.



ether, being isolated as part of an otherwise clean mixture with unreacted $(\text{Bu}_3\text{Sn})_2$ in an excellent overall yield of 92% (1.3:1 molar ratio, see ESI† S9).

In conclusion, we have developed a simple, new method for the direct transformation of P_4 into a variety of commercially and academically interesting OPCs. The reaction proceeds through a photocatalytic stannylation of white phosphorus, which generates $(\text{Bu}_3\text{Sn})_3\text{P}$ with perfect atom economy as a single, convenient P_1 intermediate using an inexpensive, commercially available distannane and a simple photocatalyst. This method can be used to prepare a variety of different products through inclusion of a range of different electrophilic substrates, and we have demonstrated that the Sn-containing byproducts of the reaction can in principle be recovered and recycled. These results expand the currently very limited range of strategies that are available for the direct functionalization of P_4 , and suggest the intriguing possibility that P_4 activation might also be achievable by reaction with other weak E–E bonds under similar photocatalytic conditions.

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Conflicts of interest

There are no conflicts to declare.

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