Photocatalysis

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Photocatalytic Arylation of P_4 and PH_3: Reaction Development Through Mechanistic Insight

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Dedicated to Professor Holger Braunschweig on the occasion of his 60th birthday

Abstract: *Detailed $^{31}P\{^1H\}$ NMR spectroscopic investigations provide deeper insight into the complex, multi-step mechanisms involved in the recently reported photocatalytic arylation of white phosphorus (P_4). Specifically, these studies have identified a number of previously unrecognized side products, which arise from an unexpected non-innocent behavior of the commonly employed terminal reductant Et_3N. The different rate of formation of these products explains discrepancies in the performance of the two most effective catalysts, $[Ir(dtbbpy)(ppy)_2][PF_6]$ (dtbbpy = 4,4′-di-tert-butyl-2,2′-bipyridine) and 3DPAFIPN. Inspired by the observation of PH_3 as a minor intermediate, we have developed the first catalytic procedure for the arylation of this key industrial compound. Similar to P_4 arylation, this method affords valuable triarylphosphines or tetraarylphosphonium salts depending on the steric profile of the aryl substituents.*

Introduction

White phosphorus (P_4) is the common precursor from which all organophosphorus compounds (OPCs) are currently prepared.[1] The enormous range of important applications of these compounds (including pharmaceuticals, agrochemicals, photoinitiators, catalysts, *et cetera*) makes P_4 one of the most important single precursors for the modern chemical industry.[2] Unfortunately, current methods for the use of elemental phosphorus suffer from major drawbacks, including difficulties in the initial preparation of P_4 from phosphate minerals as well as problems relating to phosphorus recovery and recycling.[3] Particularly significant are serious limitations in state-of-the-art methods for the transformation of P_4 into useful OPCs, which rely on wasteful and inefficient multi-step procedures involving extremely hazardous and difficult-to-handle reagents and intermediates.[4] These problems are exemplified in the syntheses of arylated phosphines (Ar_3P) and phosphonium salts (Ar_4P^+), which find important commercial applications in catalysis (among many other areas)

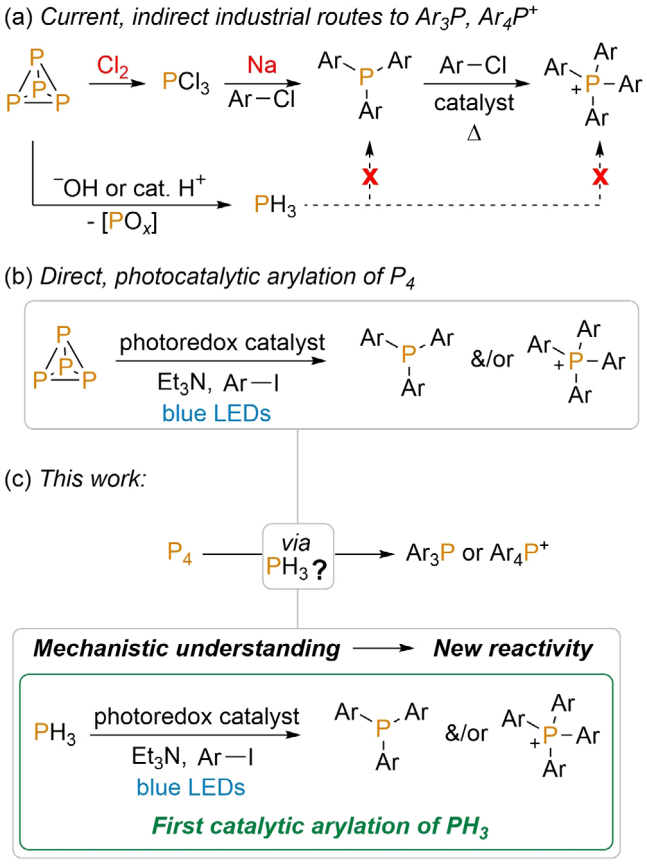

Figure 1. a) Indirect, stepwise methods for the synthesis of triarylphosphines Ar_3P and tetraarylphosphoniums Ar_4P^+ employed industrially; b) recently reported direct photocatalytic transformation of P_4 into Ar_3P and Ar_4P^+ and c) direct photocatalytic arylation of PH_3 described herein, developed based on improved mechanistic understanding of P_4 arylation.[9]

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and whose preparation involves such compounds as Cl_2, PCl_3 and molten Na (Figure 1 a).[4,5]

These deficiencies have prompted great interest in the development of alternative methodologies for the transformation of P_4,[6] and particularly those that have the potential to furnish OPCs directly in a single reaction, without the need for laborious isolation and manipulation of potentially hazardous intermediates.[7] Unfortunately, despite extensive studies leading to numerous fundamental insights, the development of such new reactions has proven exceedingly challenging. In particular, while P_4 is well known for being chemically reactive, researchers have struggled to find reactions that can selectively produce individual, useful OPCs in good yield.[8]

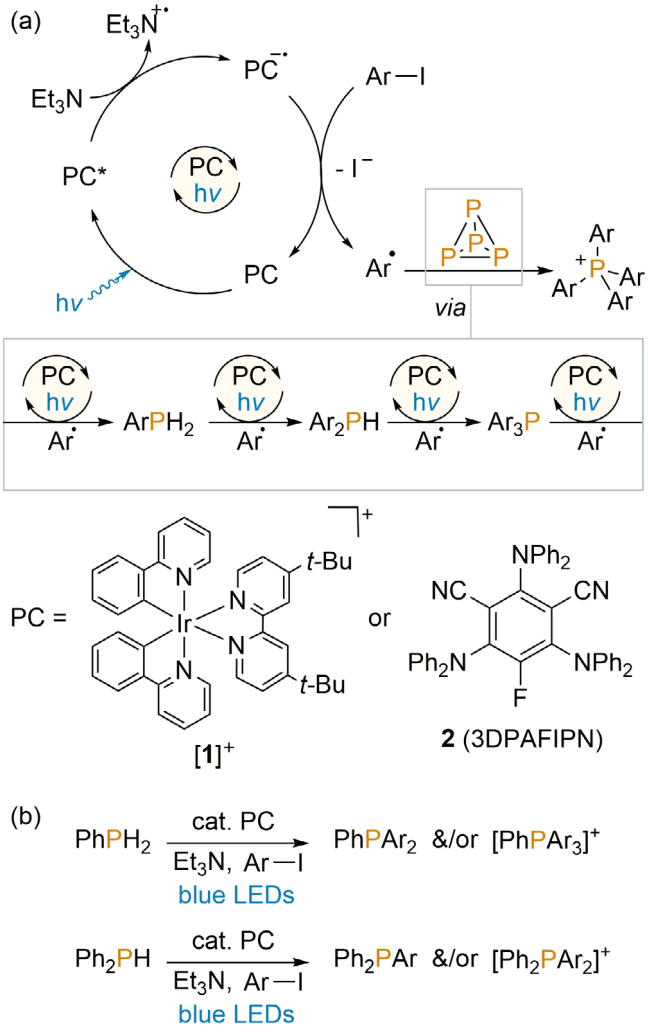
Recently, we reported a breakthrough in this area. We found that photoredox methods could be employed to successfully combine P_4 with aryl iodides (ArI) to generate the corresponding Ar_3P and Ar_4P^+ products under very mild conditions, often with markedly high selectivity (Figure 1 b).[9] This is the first example of such a catalytic procedure furnishing these products directly from P_4. Given the exponential growth in photoredox techniques reported over the past decade,[10] including for P–C bond formation in other contexts,[11] photoredox catalysis may also hold a much broader potential for the productive transformation of P_4.[12] Nevertheless, if this goal is to be successfully realised it is crucial to develop a deeper understanding of the mechanisms that underpin the existing photoredox reactivity of P_4.[13]

Herein we report a detailed NMR spectroscopic study on the mechanism of photoredox-catalytic P_4 arylation. From the results, we have been able to draw a number of significant conclusions. These include a recognition of the importance of side reactions in determining overall product yields, a rationalisation for the differing activities of precious metal and organic photocatalysts, and the identification of a viable minor reaction pathway that involves PH_3 as an early reaction intermediate. Building upon the last of these, we have been able to develop the first examples of catalytic arylation of PH_3, so providing an entirely new route to produce Ar_3P and Ar_4P^+ products starting from this industrially important synthetic intermediate (Figure 1 c).

Results and Discussion

Previous studies and open mechanistic questions

As part of our initial report of photoredox-catalysed P_4 arylation we described a series of preliminary mechanistic studies, on the basis of which we were able to propose an approximate outline mechanism for the catalytic phenylation of P_4 to Ph_4P^+.[9a] This is reproduced in Scheme 1 a, and involves a fairly typical photoredox catalytic cycle for the generation of phenyl radicals (Ph• for Ar = Ph), in which the photoredox catalyst [**1**]PF_6 (**1** = Ir(dtbbpy)$(ppy)_2$, dtbbpy = 4,4′-di-*tert*-butyl-2,2′-bipyridine, ppy = 2-(2-pyridyl)phenyl; structure shown in Scheme 1) undergoes photoexcitation by blue light, followed by reductive quenching by Et_3N (which acts as terminal reductant in this reaction), and oxidative



Scheme 1. a) Outline mechanism for photocatalytic P_4 arylation proposed previously; and b) recently reported photocatalytic P-H arylation of $PhPH_2$ and Ph_2PH.

regeneration by the substrate PhI. This last redox step prompts mesolytic fragmentation of the aryl halide substrate, generating radicals Ph•. These can then add to P_4 to generate in sequence $PhPH_2$, Ph_2PH, Ph_3P and Ph_4P^+, with the formation of these intermediates being observable by $^{31}P\{^1H\}$ NMR spectroscopy. The H atoms required for formation of $PhPH_2$ and Ph_2PH were proposed to derive from the reductant Et_3N, presumably *via* direct abstraction of H• (HAT) or H^+ following oxidation to $Et_3N^{\bullet+}$. As part of the study described herein it was possible to confirm this hypothesis through use of deuterium-labelled Et_3N-d_{15}, which led to clear deuterium incorporation into these intermediates (see Section 3.6 of the Supporting Information for further details). Subsequent loss of these H atoms was proposed to proceed by formation of ArH (observed as a byproduct by ^1H and ^2H NMR spectroscopy).[14]

Each of the individual arylation steps was previously confirmed to be photocatalytic. Indeed, in a recent follow-up study, we reported that the same methodology could be optimised to use $PhPH_2$ and Ph_2PH as starting materials for

the generation of unsymmetrically substituted products (e.g. $PhPAr_3^+$, $Ph_2PAr_2^+$; Scheme 1b).[9b] This report also showed that the previously used precious metal catalyst [**1**]PF_6 could be replaced by the inexpensive and easily accessible organic catalyst 3DPAFIPN (**2**; structure shown in Scheme 1) for the arylation of both P_4 and $PhPH_2$/Ph_2PH.[15]

Despite the superficial simplicity of the catalytic cycle shown in Scheme 1a it is clear that the overall mechanism is highly complex (we have emphasised previously that exhaustive phenylation of one equivalent of P_4 requires the cleavage of six separate P-P bonds, formation of 16 new C-P bonds, and consumption of at least 16 equivalents each of PhI and Et_3N) and that several important questions remain to be answered. From among these, at the outset of this study we identified three that are of particular significance:

1) *Is it possible to identify any other intermediate(s) formed prior to $PhPH_2$?* Although $PhPH_2$ is the first P-containing intermediate that it has been possible to observe during the phenylation of P_4 thus far, it clearly cannot be the first such intermediate. Notably, by identifying $PhPH_2$ and Ph_2PH as intermediates it has been possible to develop new functionalisation reactions of these substrates,[9b] which might also be true for any earlier intermediates.

2) *Is it possible to account for missing ^{31}P intensity in these reactions?* Preliminary *in situ* $^{31}P\{^1H\}$ NMR monitoring has shown that initial consumption of P_4 is far faster than the formation of the first observable P-containing intermediate ($PhPH_2$). Similarly, standard $^{31}P\{^1H\}$ spectroscopic measurements of the final reaction mixtures suggest that formation of the target products (e.g. Ar_3P, Ar_4P^+) is typically very clean (no other P-containing species present, including P_4), yet conversion to these products is consistently less than quantitative based on the initial amount of P_4.

3) *Can discrepancies in performance between catalysts [**1**]PF_6 and **2** be explained?* Although their photoredox properties are very similar, [**1**]PF_6 has been found to give consistently higher product conversions for P_4 arylation than **2**. Conversely, **2** has been found to provide better conversions than [**1**]PF_6 for analogous arylations starting from $PhPH_2$/Ph_2PH.

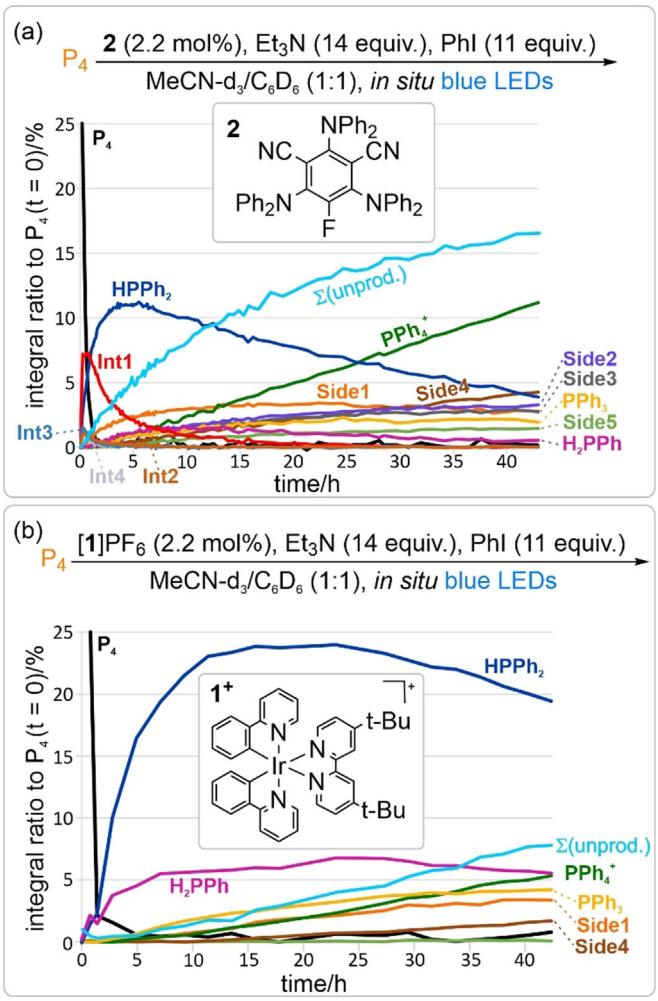


Figure 2. Reaction profiles showing the evolution of P atom speciation during the light-driven phenylation of P_4 (0.1 mmol scale) catalysed by **2** (a) or [**1**]PF_6 (b), as assessed by time-resolved $^{31}P\{^1H\}$ NMR spectroscopy. Equivalents of reagent (equiv) and catalyst loadings (in mol%) are defined per P atom. Σ(unprod.) indicates the sum of intensities for unproductive side-products **Side1**–**Side5**. For a more comprehensive display of the kinetics see Section 3.9.1 in the Supporting Information.

Identifying new intermediates and side-products during the arylation of P_4

Having previously shown $^{31}P\{^1H\}$ NMR monitoring to be a valuable tool for the investigation of the P_4 arylation reaction,[9a] we reasoned that answers to our question set might be found through more detailed NMR spectroscopic analysis. For consistency with previous studies, arylation using PhI was again chosen as the simplest model system. To begin, the phenylation of P_4 using organic photocatalyst **2** was monitored over time, to provide a comparison with the analogous experiment already performed using [**1**]PF_6 as catalyst.[9a,16] As expected, a similar overall reaction profile was observed (Figure 2a), with rapid consumption of P_4 followed by intermediate formation of $PhPH_2$, Ph_2PH and Ph_3P, and ultimately formation of Ph_4P^+ as the major reaction product. Observation of a photo-CIDNP effect in the corresponding ^1H NMR spectra was also consistent with previous observations using [**1**]PF_6 (see Section 3.8 of the Supporting Information for more details).[9a,17] Nevertheless, some qualitative differences between the two catalysts could clearly be resolved. In particular, formation of the early intermediates $PhPH_2$ and Ph_2PH appears to peak significantly more quickly using **2**, while the magnitude of these peaks is reduced (*c.f.* Figure 2a,b).

More dramatically, in addition to the expected intermediates Ph_xPH_{3-x} ($x = 1$–3), $^{31}P\{^1H\}$ NMR monitoring clearly showed the formation of a significant number of other minor peaks during the reaction catalysed by **2** (for representative example spectra, see Figure 3a). Some of these (designated **Int1**–**Int4**) were identified as intermediate species (either for productive or unproductive processes) based upon their concentration profile over time, while others (designated **Side1**–**Side5**) were identified as side-products and were

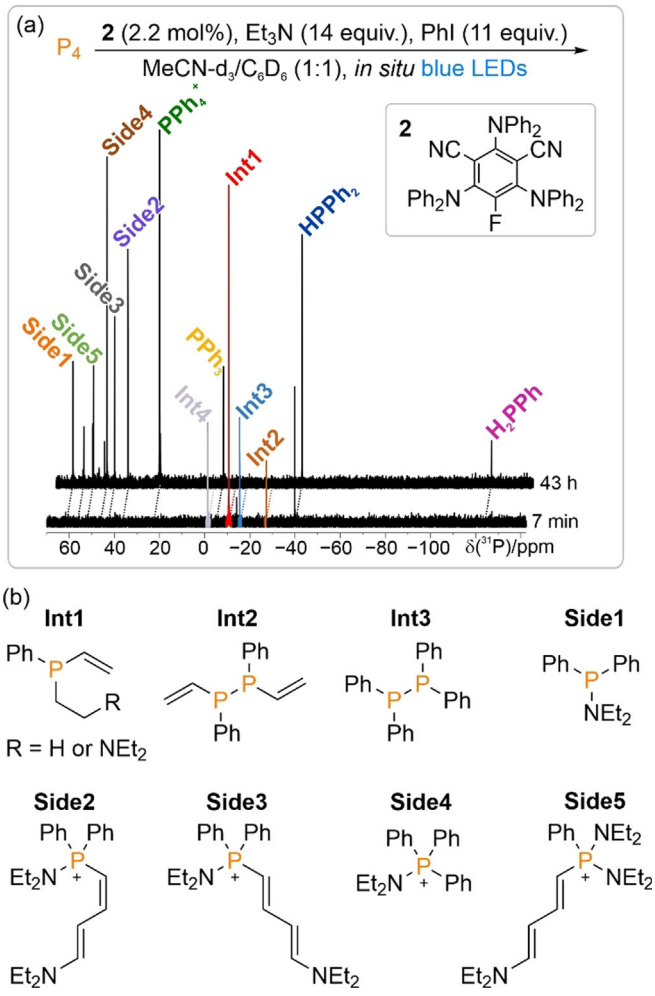


Figure 3. Example $^{31}P\{^{1}H\}$ NMR spectra showing the formation of minor intermediates (**Int1**–**Int4**) and side-products (**Side1**–**Side5**) during the light-driven phenylation of P_4 (0.1 mmol scale) catalysed by organocatalyst **2** (a); and tentatively proposed structures of these species based on *in situ* NMR data (see Sections 3.10 and 3.11 of the Supporting Information for more information) (b).

persistent until the end of the reaction (Figure 2a). The same side-products (**Side1**–**Side5**) could also subsequently be detected in the reaction catalysed by [**1**]PF_6, but at appreciably lower concentrations (Figure 2b). Nevertheless, the combined intensity of these signals accounts for a significant proportion of the overall ^{31}P intensity in the final reaction spectra, and it seems feasible that there may be further unresolved signals of lower intensity, which could sum to a further significant value (*vide infra*).

These observations suggest a clear explanation for less-than-quantitative target product formation highlighted above, with maximum formation of the final target products being limited by the formation of a collection of minor side products in amounts that are individually insignificant, but collectively substantial. Moreover, the fact that far greater amounts of these side-products are observed when using the organocatalyst **2** provides a rationale for the observation that **2** furnishes consistently poorer final product conversions for the arylation of P_4, despite being a more productive catalyst for the optimised synthetic arylations of the "downstream" intermediates $PhPH_2$ and Ph_2PH (for a discussion of catalyst performance in these latter reactions see Section 3.9.3 of the Supporting Information).

Plausible structures of the species **Int1**–**Int3** and **Side1**–**Side5** are shown in Figure 3b and are based upon detailed *in situ* NMR studies including 2D techniques and proton-coupled ^{31}P spectra which are presented in the Supporting Information (Sections 3.10 and 3.11), alongside discussion of possible mechanisms of formation. As an illustrative example, the product **Side1** could be assigned based on a combination of its ^{31}P chemical shift (suggestive of a Ph_2PNR_2 species), long range ^{1}H-^{31}P correlation experiments (showing correlations between the ^{31}P resonance and ^{1}H signals at chemical shifts consistent with Ph and CH_2Me peaks), and comparison with literature data.

Interestingly, the majority of these species appear to be derived from non-innocent behaviour of the Et_3N terminal reductant (with the notable exception of **Int3**, Ph_4P_2, which was also observed in our previous investigation of the **2**-catalysed reaction of Ph_2PH with cyclohexyl iodide, and was proposed to arise through dimerization of transiently-formed radicals $Ph_2P^{\bullet}$).[9b] Given that Et_3N is widely used as a "privileged" terminal reductant in photoredox transformations, and that [**1**]PF_6 and **2** have also been used to catalyse many other photoredox reactions, these results suggest that similar patterns of non-selective side-reactivity could be an underappreciated but highly significant limiting factor in many other photoredox transformations (indeed, related non-innocent side reactions have previously been highlighted in some other catalytic reactions).[18] In the absence of the convenient ^{31}P NMR handle, these would likely be extremely challenging to detect. Minimisation of these side reactions is a clear avenue for further reaction optimisation.[19]

To try and identify further reaction intermediates—particularly those that may form in the early stages of the reaction—additional monitoring experiments were carried out on reactions performed at lower temperatures and using higher catalyst loadings. It was anticipated that transient, early intermediates might be better able to accumulate under these conditions and, indeed, several further $^{31}P\{^{1}H\}$ resonances could be observed (see Figure 4a; designated **Int5**–**Int8**; again, these may be intermediates for either productive or unproductive processes), and plausible corresponding chemical structures assigned are depicted in Figure 4b (see also Section 3.11.1 of the Supporting Information). The proposed structures of **Int5**–**Int7** further emphasise the non-innocent behaviour of the Et_3N reductant.

PH_3 as a substrate for photocatalytic arylation

The specific observation of PH_3 as one of the above intermediate signals (**Int8**; readily assigned on the basis of its characteristic chemical shift and binomial quartet splitting in the proton-coupled ^{31}P spectrum, see Figure 4a) was particularly intriguing.[3b] Although our previous mechanistic proposals (e.g. Scheme 1a) had assumed $PhPH_2$ to be the first P_1 intermediate formed, this result—combined with our previ-

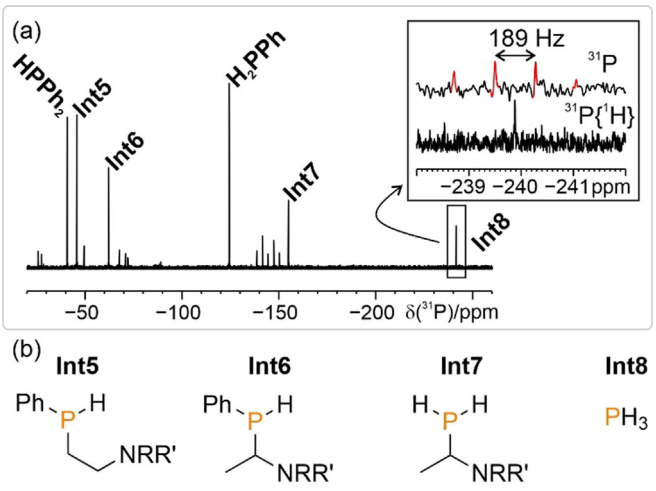


Figure 4. a) $^{31}P\{^{1}H\}$ NMR spectrum showing the formation of further intermediates (**Int5-Int8**) of the light-driven phenylation of P_4 (0.1 mmol scale) catalysed by [**1**]PF_6. The spectrum was recorded in the dark after an illumination period of 30 min at 273 K (see also Section 3.11.1 of the Supporting Information). b) Proposed structures of **Int5**–**Int8** observed during the light-driven phenylation of P_4 catalysed by [**1**]PF_6 and **2** at low temperatures and high catalyst loadings.

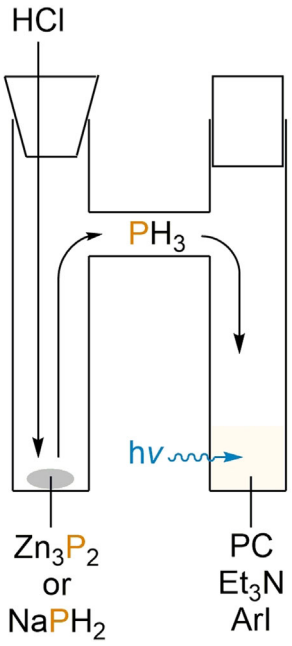


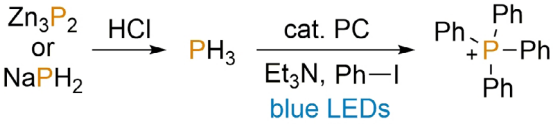
Figure 5. Schematic representation of the two-chambered apparatus used to investigate the photocatalytic phenylation of PH_3, generated by *in situ* acidification of suitable solid precursors.

ous observation that PH_3 can be formed upon irradiation of a combination of P_4, Et_3N and [**1**]PF_6 *in the absence of ArI*—suggested an alternative synthetic possibility. Specifically, it was queried whether PH_3 could in fact be a key intermediate formed *prior* to arylation: that is, whether arylation of P_4 could proceed *via* initial Et_3N-mediated reduction to PH_3,[20] with arylation only subsequently occurring. Notably, such a possibility would have broad implications beyond the immediate mechanistic significance. PH_3 is a major synthetic intermediate, employed industrially for the preparation of many important phosphine and phosphonium derivatives. However, these syntheses proceed exclusively through the hydrophosphination of unsaturated substrates, which limits the scope of accessible products and thereby excludes the formation of aryl-substituted derivatives (Ar_3P, Ar_4P^+). Indeed, efficient, direct arylation of PH_3 remains a long-unmet synthetic goal that, though related, is distinct from the target of direct P_4 functionalisation.[3c,4,21]

To this end, it was decided to investigate the deliberate use of PH_3 as a substrate for our photoredox-catalysed arylation methodology. For reasons of practical simplicity, PH_3 was not employed directly, but rather generated *in situ* using a two-chambered apparatus, inspired by a recent report by Ball et al. (Figure 5).[22] Addition of aqueous HCl to solid Zn_3P_2 in one chamber liberates gaseous PH_3, which can diffuse into the second chamber. This chamber contains the remaining components of the photocatalytic reaction mixture and is stirred under continuous blue LED irradiation (with concomitant water cooling to maintain approximately ambient temperature).

Gratifyingly, initial experiments using catalytic [**1**]PF_6 and reaction conditions identical to those used previously in the optimised phenylation of P_4 unambiguously confirmed the formation of Ph_4P^+ in modest yields (Table 1, entry 1). This result clearly illustrates the feasibility of PH_3 as an intermediate *en route* to arylated products and to our knowledge is the first example of the successful catalytic arylation of PH_3. Control experiments confirmed that all reaction components

Table 1: Photocatalytic phenylation of PH_3.



Entry[a]	PH_3 source (mmol)	PC (mol%)	*t* [h]	Solvent	Conversion to Ph_4P^+ [%]
1	Zn_3P_2 (0.05)	[**1**]PF_6 (2)	18	MeCN/PhH (3:1)	17
2	Zn_3P_2 (0.15)	**2** (10)	48	MeCN/PhH (3:1)	23
3	Zn_3P_2 (0.15)	[**1**]PF_6 (2)	48	MeCN	30
4[b]	Zn_3P_2 (0.15)	[**1**]PF_6 (2)	48	MeCN	35
5[b]	$NaPH_2$ (0.1)	[**1**]PF_6 (2)	24	MeCN	41
6[c]	$NaPH_2$ (0.1)	[**1**]PF_6 (2)	24	MeCN	29
7[c,d]	$NaPH_2$ (0.1)	[**1**]PF_6 (2)	24	MeCN	68

[a] Reactions performed using a 20 mL two-chambered apparatus described in Figure 5, using 12.5 equiv HCl, 11 equiv PhI, 14.4 equiv Et_3N in 2.0 mL solvent under blue LED irradiation and N_2 atmosphere. [b] A 10 mL two-chambered apparatus was used. [c] A 10 mL single-chambered apparatus was used. [d] No HCl was added. Equivalents of reagent (equiv) and catalyst loadings (in mol%) are defined per P atom.

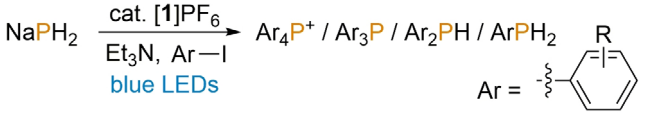
([**1**]PF_6, Et_3N, light) were necessary to achieve appreciable product formation (Table S1, SI). Catalytic formation of Ph_4P^+ could also be achieved using organocatalyst **2** instead of [**1**]PF_6 (Table 1, entry 2), illustrating that this reactivity is not dependent on the use of a precious metal, and is mechanistically feasible for an organocatalysed reaction.

Conversion to the target Ph_4P^+ could be significantly increased through modification of the reaction time, solvent, and concentration (Table 1, entry 3 and Table S2, SI). Although these conversions are still appreciably lower than those obtained previously when starting from P_4, this may be attributable at least in part to differences in experimental setup. In particular, the need for gaseous PH_3 to diffuse between reaction chambers before dissolving in the reaction solution is expected to significantly impact the rate of reaction. This conclusion was supported by reactions performed using a two-chamber apparatus of reduced volume, which led to a further improvement in performance (Table 1, entry 4; for full details of the apparatus see Section 2.1 of the Supporting Information). An additional improvement was observed upon replacement of Zn_3P_2 with $NaPH_2$, as an alternative source of PH_3 upon acidification (Table 1, entry 5).[23]

To further mitigate problems associated with gas transfer of PH_3, the use of a single-chambered experimental apparatus was pursued, within which it was hoped that addition of acid would trigger release of PH_3 directly into the photocatalytic reaction solution (for full details see Section 2.2.1 of the Supporting Information). Disappointingly, use of this apparatus in combination with $NaPH_2$/HCl as a source of PH_3 did not lead to an improvement in reaction outcome, although clear catalytic formation of Ph_4P^+ was once again observed (Table 1, entry 6). Gratifyingly, however, when this reaction was repeated in the absence of HCl significantly improved results were observed, with very good conversion to the target product achieved following slight further optimisation (Table 1, entry 7 and Table S3, SI). Thus, the conjugate base of PH_3 appears to be a highly effective and convenient synthetic surrogate for PH_3 in these reactions, allowing catalytic arylation to be performed in a practically convenient manner while achieving synthetically relevant conversion and selectivity.

Having identified an optimised set of reaction conditions for the [**1**]PF_6-catalysed phenylation of PH_3, the use of other, substituted aryl iodides was investigated (Table 2). Satisfyingly, a range of other substrates ArI could be employed successfully, including examples bearing both electron-donating and electron-withdrawing groups and with varying steric bulk. These reactions yielded either phosphonium salts Ar_4P^+ or tertiary phosphines Ar_3P, with the latter being favoured for more sterically hindered substrates (notably 2-iodotoluene, which provided good conversion to the important ligand (o-tol)$_3$P with good conversion and excellent selectivity; o-tol = 2-methylphenyl; Table 2, entry 2),[5] as well as electron-deficient substrates (such as methyl 4-iodobenzoate; Table 2, entry 7). Notably, the particularly bulky substrate MesI (Mes = 2,4,6-trimethylphenyl) failed to reach even the tertiary phosphine, instead producing the primary and secondary phosphines $MesPH_2$ and Mes_2PH as the only

Table 2: Photoredox arylation of $NaPH_2$ (as a surrogate for PH_3) catalysed by [**1**]PF_6.



Entry[a]	R	Conversion to Ar_4P^+ [%]	Conversion to Ar_3P [%]	Conversion to Ar_2PH [%]	Conversion to $ArPH_2$ [%]
1	H	77	–	–	–
2	2-Me	–	63	–	–
3	3-Me	61	6	–	–
4	4-Me	64	< 5	–	–
5	2-CO_2Me	–	10	–	–
6	3-CO_2Me	29	< 5	–	–
7	4-CO_2Me	–	32	–	–
8	2-SMe	–	13	–	–
9	2-OMe	–	42	–	–
10	3-OMe	53	< 5	–	–
11	4-OMe	39	6	–	–
12	2-CF_3	–	–	–	–
13	3-CF_3	12	7	–	–
14	4-CF_3	7	19	–	–
15	2,4,6-Me_3	–	–	11	17
16	Ph_3SnCl[b]	–	55[c]	–	–

[a] Reactions performed using 0.1 mmol $NaPH_2$, 2 mol% [**1**]PF_6, 11 equiv ArI, 15 equiv Et_3N in 2.0 mL MeCN under blue LED irradiation and N_2 atmosphere for 24 h. [b] Ph_3SnCl instead of ArI. [c] $(Ph_3Sn)_3P$ formed instead of Ar_3P.

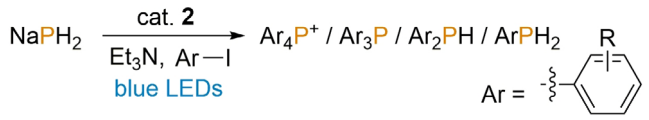
products detected by standard $^{31}P\{^1H\}$ NMR spectroscopic measurements (Table 2, entry 15). The heteroatomic substrate Ph_3SnCl could also successfully be employed, providing reasonable, selective conversion to the interesting "P^{3-}" synthon $(Ph_3Sn)_3P$ without any further reaction optimisation (Table 2, entry 16). In all cases the observed trends in reactivity and selectivity are in excellent agreement with those noted previously for the photocatalytic arylation of P_4.[9]

Having established the scope of the [**1**]PF_6-catalysed reaction, the use of the less expensive and more abundantly available, sustainable organic photoredox catalyst **2** was also investigated. Gratifyingly, after only minor further reaction optimisation (Table S4, SI), good conversions could also be achieved using this more practical, precious metal-free catalyst, under similar conditions (Table 3). In general, both catalysts achieve similar conversions, and the same trends in product selectivity are observed with respect to the substrates' steric and electronic properties. Nevertheless, in several cases an appreciably superior preference is observed for either the metallo- or organo-catalyst (for example: compare entries 2 and 9 in both Table 2 and Table 3), indicating that the choice of catalyst can be tailored to the specific target product.

Mechanisms of photocatalytic arylation

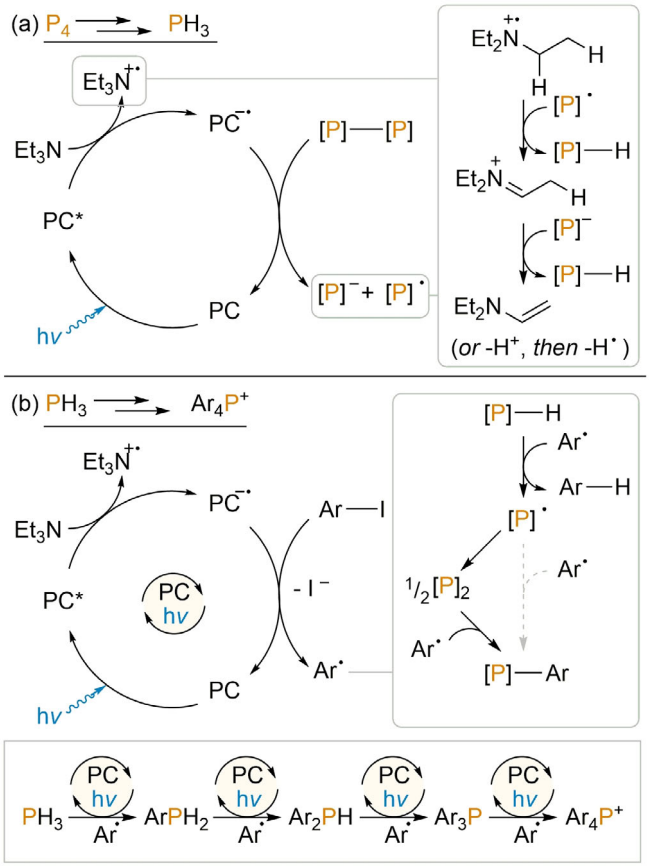
Based on our prior studies of photocatalytic P_4, $PhPH_2$ and Ph_2PH arylation, as well as the studies described herein, it is possible to propose complete mechanistic courses for both

Table 3: Photoredox arylation of $NaPH_2$ (as a surrogate for PH_3) catalysed by organocatalyst **2**.



Entry[a]	R	Conversion to Ar_4P^+ [%]	Conversion to Ar_3P [%]	Conversion to Ar_2PH [%]	Conversion to $ArPH_2$ [%]
1	H	72	–	–	–
2	2-Me	–	51	–	–
3	3-Me	51	< 5	–	–
4	4-Me	56	–	–	–
5	2-CO_2Me	–	7	< 5	–
6	3-CO_2Me	20	< 5	–	–
7	4-CO_2Me	–	9	–	–
8	2-SMe	–	29	–	–
9	2-OMe	–	52	–	–
10	3-OMe	72	7	–	–
11	4-OMe	34	14	–	–
12	2-CF_3	–	–	–	–
13	3-CF_3	30	6	–	–
14	4-CF_3	< 5	18	–	–
15	2,4,6-Me_3	–	–	7	19
16	Ph_3SnCl[b]	–	41[c]	–	–

[a] Reactions performed using 0.1 mmol $NaPH_2$, 10 mol% **2**, 13 equiv ArI, 16 equiv Et_3N in 2.0 mL MeCN under blue LED irradiation and N_2 atmosphere for 24 h. [b] Ph_3SnCl used instead of ArI. [c] $(Ph_3Sn)_3P$ formed instead of Ar_3P.



Scheme 2. Complete proposed mechanisms for the photocatalytic reduction of P_4 to PH_3 in the absence of ArI (a); and the photocatalytic arylation of PH_3 in the presence of ArI (b). Here, [P]-[P] indicates a generic P-P bond derived from P_4 and [P]-H indicates a generic P–H bond derived from PH_3. PC = $[\mathbf{1}]^+$ or **2**.

the photocatalytic formation of PH_3 from P_4 and Et_3N, and the photocatalytic arylation of PH_3 (Scheme 2). For the former, the photoexcited state of the photocatalyst PC (PC = $[\mathbf{1}]^+$ or **2**) undergoes reductive quenching by Et_3N (confirmed previously by fluorescence quenching experiments) to generate $Et_3N^{+\bullet}$ and the reduced catalyst $PC^{\bullet-}$. Thus generated, $PC^{\bullet-}$ can effect single electron reduction of one of the P-P bonds present in P_4 (confirmed previously by UV/Vis spectroelectrochemistry) to generate a phosphorus-centred radical and anion. Abstraction of $H^\bullet$ and H^+ respectively by these species from $Et_3N^{+\bullet}$ (Et_3N having been established as the ultimate H atom source for this chemistry; *vide supra*; for the corresponding *in situ* NMR study applying fully deuterated Et_3N see Section 3.6 in the Supporting Information) then generates new P–H bonds and ultimately PH_3.

Arylation of PH_3 is proposed to occur *via* an analogous mechanism to that already established for P-H arylation of the "downstream" intermediates $PhPH_2$ and Ph_2PH. Reduction of ArI by $PC^{\bullet-}$ (generated as outlined above) generates aryl radicals $Ar^\bullet$ that can abstract $H^\bullet$ to generate transient $^\bullet PH_2$ which can then combine with a second equivalent of $Ar^\bullet$ to produce $ArPH_2$ (most likely *via* intermediate formation of the dimer P_2H_4; *c.f.* our previous observation of Ph_4P_2 during P-H functionalisation of Ph_2PH).[9b] Analogous, subsequent arylation steps then generate in turn Ar_2PH and Ar_3P (and, for certain Ar, Ar_4P^+), as established in our previous investigations. Formation of this sequence of intermediates has been further confirmed by NMR monitoring of the "single chamber" arylation of $NaPH_2$ (Figure 6).

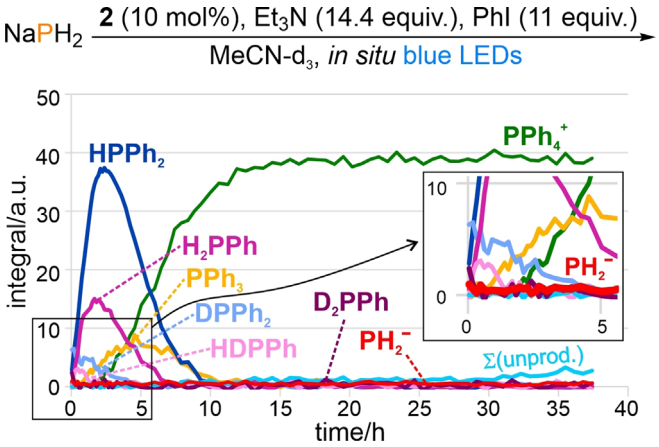
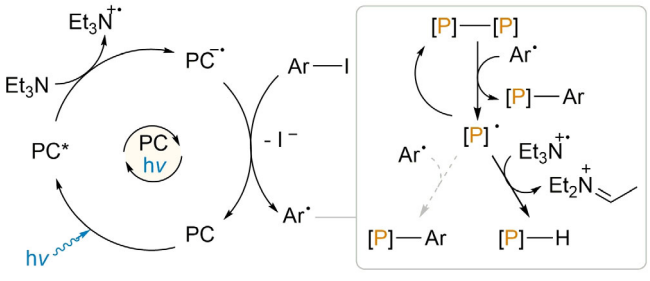


Figure 6. Reaction profile showing the evolution of P atom speciation during the light-driven phenylation of $NaPH_2$ (0.1 mmol scale) catalysed by organocatalyst **2**, as assessed by time-resolved $^{31}P\{^1H\}$ NMR spectroscopy. Equivalents of reagent (equiv) and catalyst loadings (in mol%) are defined per P atom. Σ(unprod.) indicates the sum of intensities for unproductive side-products **Side1**–**Side5**. In the magnified region, the course of PH_2^- is highlighted as a thicker line to emphasize the very low amounts present throughout.

Notably, the reaction profile in Figure 6 shows that only small amounts of $NaPH_2$ are dissolved at any specific time (PH_2^-), and also that the sequential reaction steps leading to PPh_4^+ proceed very cleanly with nearly no side product formation (*c.f.* Figure 2 for analogous, less selective reactions starting from P_4). Based on this apparent correlation it was speculated that using lower concentrations of other mono-phosphorus starting materials might also provide cleaner reactions, and thus higher eventual yields. And indeed, NMR investigations of the light-driven arylation of H_2PPh (applied in different concentrations) confirmed this hypothesis by showing that the total yield of side products increases with increasing concentration of starting material, alongside a concomitant decrease in yield of the final product (for a more comprehensive discussion of side product formation during the arylation of $PhPH_2$, see Section 3.9.4 in the Supporting Information).

Competing mechanisms of P_4 arylation

Taken together, the elementary steps outlined above (reduction of P_4 to PH_3 and its subsequent arylation) provide a plausible alternative mechanistic proposal for our previously reported catalytic arylation of P_4. Nevertheless, the mechanistic complexity of these reactions should again be acknowledged, and several specific observations suggest that these are unlikely to be the only kinetically viable elementary mechanistic steps. For example, it was noted in our original report that upon irradiation in the presence of [**1**]PF_6 and Et_3N, P_4 is consumed more quickly in the presence of PhI than in its absence, with the reverse being observed for consumption of PhI in the presence/absence of P_4. While the latter trend is easily explained based upon the above mechanism (since PhI must compete with P_4 to react with $PC^{\bullet-}$), the former is more difficult to account for. Moreover, attempts to quantify the PH_3 formed during the photocatalytic reaction between P_4 and Et_3N in the absence of ArI suggest this to be a rather inefficient process that produces PH_3 in only very low yield (see Section 3.12 of the Supporting Information for full details). It is therefore likely that reaction with Ph$^\bullet$ can provide an alternative means by which the P-P bonds of P_4 are broken (Scheme 3), in line with our initial mechanistic hypothesis.[24] We thus propose that initial degradation of the P_4 tetrahedron to P_1 species can proceed through a combination of both pathways, to generate a mixture of PH_3 and $ArPH_2$.[25] The relative rates, and hence importance, of these competing mechanistic routes is likely to depend strongly on the identity of the arene substrate (for example, more hindered aryl radicals may add more slowly to P_4, and so render this pathway less competitive).



Scheme 3. Proposed alternative initial mechanism for the photocatalytic transformation of P_4 in the presence of ArI. Here, [P]-[P] indicates a generic P-P bond derived from P_4.

Conclusion

Detailed NMR spectroscopic studies have been used to provide a significantly deeper and more comprehensive understanding of the mechanism of our recently reported, unprecedented direct photocatalytic arylation of P_4. Despite the complexity of this elaborate transformation, it is now possible to propose a plausible and comprehensive set of elementary steps for this reaction, supported by experimental observations. In addition to these primary productive steps, it has been shown that a wide variety of competing side reactions are relevant to the overall course of the reaction, resulting in of a large number of minor side products and intermediates. While these products are present in individually insignificant quantities they sum to an appreciable fraction of the overall P-containing reaction products, and their formation therefore explains the inability of these transformations to provide quantitative yields of their target products, despite full consumption of starting material and apparently clean conversion. Moreover, the use of the organophotocatalyst **2** to mediate these reactions instead of the iridium catalyst [**1**]PF_6 has been shown to significantly increase the prevalence of these side products which provides an explanation for its poorer catalytic performance in P_4 arylation, despite other investigations showing it to be a superior catalyst for the closely related arylation of $PhPH_2$ and Ph_2PH. These side products seem to be primarily derived from unexpected side reactions of the Et_3N reductant (or the aminium, iminium or enamine oxidation products thereof). Given the widespread use of Et_3N as an electron donor in photoredox chemistry, these results provide further evidence that similar side reactions may have an underappreciated limiting effect on reaction yields for many other transformations. Based on this realisation, current efforts are being made to replace Et_3N with a "better-behaved" combination of reductant and hydrogen source, to facilitate the desired transformation while minimising undesired side reactivity.

Alongside this mechanistic insight, based on the detection of PH_3 as an additional intermediate, these studies have also enabled the development of an entirely new photocatalytic transformation. Specifically, the first examples of the catalytic arylation of PH_3 have been developed, which allow for the unprecedented direct transformation of this key industrial P_1 precursor into a sterically and electronically diverse range of valuable triarylphosphines and tetraarylphosphonium salts. Notably, this reaction does not require a precious metal catalyst, and works well using 3DPAFIPN as an inexpensive and more sustainable organic photoredox catalyst.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: arylation · NMR spectroscopy · phosphine · photoredox catalysis · white phosphorus

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[19] Note however that previous screening efforts have highlighted the importance of using a reductant that can also act as a source of H atoms (presumably to facilitate formation of intermediates including $PhPH_2$ and Ph_2PH), so replacement of Et_3N with alternative reductants is a non-trivial task.
[20] For reference, the standard reduction potential for aqueous reduction of P_4 to PH_3 is −0.063 V vs. SHE, which is well within the range accessible by typical photoredox catalysis. See J. R. Rumble, *CRC Handbook of Chemistry and Physics*, CRC, Boca Raton, **2021**.
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[23] This may be due to more rapid release of PH_3 by $NaPH_2$, leading to higher PH_3 partial pressures within the reaction apparatus.
[24] Indeed, we have previously proposed that P-H alkylation of Ph_2PH may proceed *via* analogous radical attack on the P-P bond of intermediately-formed P_2Ph_4. See also the similar mechanistic steps shown in Scheme 2b.
[25] In principle, the use of aryl radicals Ar• to facilitate the degradation of P_4 could also result in formation of Ar_2PH and Ar_3P as direct products, although formation of these higher phosphines is likely to be less favoured on steric grounds. For Ar=Ph, direct formation of Ph_3P as a major pathway is also seemingly excluded by the kinetic profiles of these reactions, which show that initial formation is very slow relative to $PhPH_2$ and Ph_2PH. For Ph_2PH, which forms more quickly, it is harder to confidently distinguish between formation as a P_1 product directly from P_4, and formation by rapid arylation of $PhPH_2$.

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Research Articles

Photocatalysis

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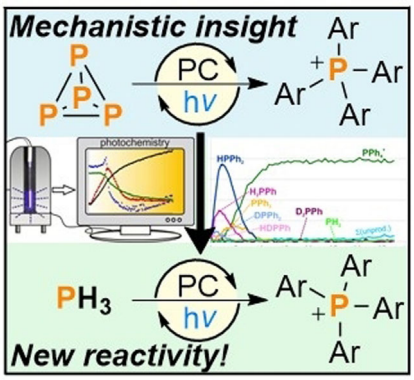
Photocatalytic Arylation of P_4 and PH_3: Reaction Development Through Mechanistic Insight



$^{31}P\{^1H\}$ NMR spectroscopic studies provide significant, new insights into the mechanism of the recently reported photocatalytic arylation of white phosphorus (P_4). Through the first-time observation of a series of reaction intermediates, these studies have also inspired the development of the first examples of direct, catalytic arylation of PH_3, which is a key synthetic intermediate for industrial phosphorus chemistry.

