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DOI: 10.1039/D4SC08521C

ARTICLE

Unlocking the Reactivity of the C-In Bond: Alkyl Indium Reagents as a Source of Radicals Under Photocatalytic Conditions

Anton A. Gladkov,[ab] Vitalij V. Levin,[a] Demian Y. Cheboksarov,[ab] Alexander D. Dilman[a]*

Received 00th January 20xx,
Accepted 00th January 20xx

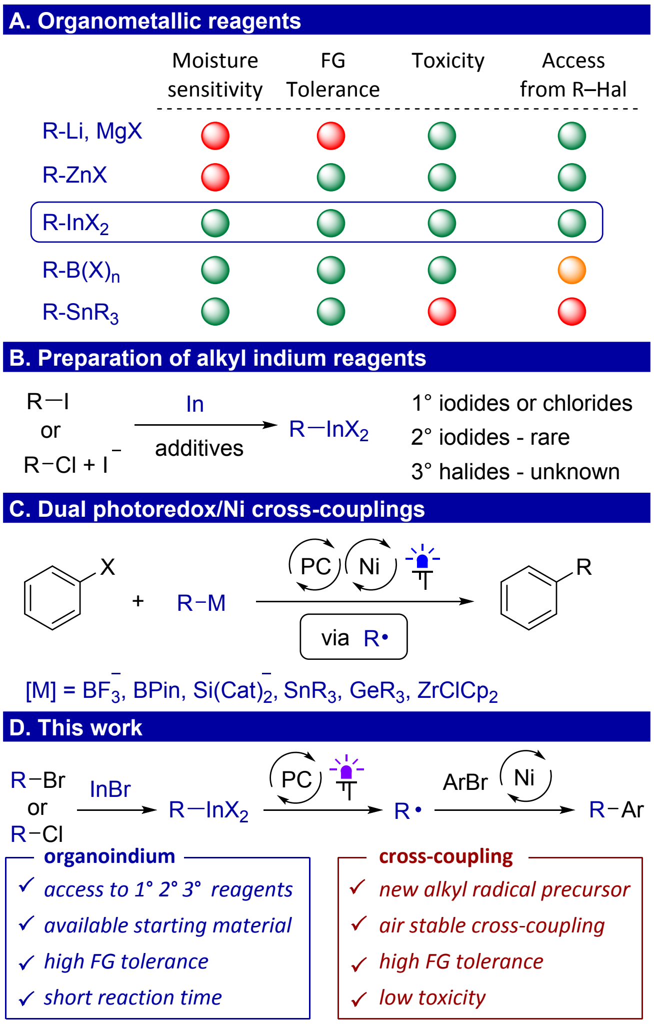
DOI: 10.1039/x0xx00000x

Generation of organic radicals from organometallic compounds is a key step in metallaphotoredox cross-coupling reactions. The ability of organoindium compounds to serve as sources of alkyl radicals under light promoted oxidative conditions is described. Organoindium reagents were used in dual photocatalytic/nickel cross-coupling with aryl bromides. These reagents can be conveniently obtained from primary, secondary and tertiary alkyl bromides and chlorides using novel indium(I) bromide/lithium bromide system. Both steps, the formation of organoindiums and their cross-coupling are insensitive towards air, moisture and tolerate wide variety of functional groups.

Introduction

Organometallic compounds involving alkyl lithium, magnesium and zinc reagents have found widespread applications as nucleophilic reagents.[1,2] However, the increased sensitivity of these reagents to moisture and air, coupled with incompatibility of lithium and magnesium reagents with crucial functional groups such as hydroxyl, carbonyl group and nitrile, limits their applicability in organic synthesis (Scheme 1A). In contrast, less polar boron, silicon and tin reagents demonstrate tolerance to a multitude of functional groups and can be handled in air, but they are poorly reactive and require activation. The modern method of activation is conversion of organometallics to a radical, which has expanded the synthetic applications of alkyl boron[3,4] and zinc[5-10] reagents. The range of non-polar reagents also includes organoindium compounds, which have previously been considered to be rare reagents.[11] It is located in close proximity to tin in the periodic table, and therefore, chemical properties of their organic derivatives are expected to be similar. However, an indisputable advantage of organoindium reagents is their low toxicity. [12] Another point is an opportunity to access alkyl indium reagents directly from organic halides by insertion of indium into the carbon-halide bond. However, the latent synthetic potential of these reagents as source of radicals under photocatalytic conditions has not yet been realized due to the low polarity of the C-In bond and the limited scope of accessible alkyl indium reagents.

The preparation and synthetic applications of aryl,[13-17] allyl,[18] allenyl,[19,20] and indium enolates[21] have been well studied. This is due to the ease of production and increased nucleophilicity of these compounds. Despite the progress achieved with organoindiums mentioned above, methods for the preparation and applications of alkyl indium reagents are still limited. In earlier reports, they were s prepared by transmetallation from organolithium or organomagnesium reagents.[22,23] Later, the reaction of alkyl halides with elemental indium was used, but due to low activity of indium metal, additives have to be used such as copper,[24,25] silver,[26] cobalt,[27] cesium[28] or indium[29] salts, and elemental iodine[30] (Scheme1B). Primary alkyl iodides were typically used, while reaction of primary



Scheme 1. Organometallic reagents.

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[a] N. D. Zelinsky Institute of Organic Chemistry, 119991 Moscow, Leninsky prosp. 47, Russian Federation. E-mail: adil25@mail.ru

[b] Lomonosov Moscow State University, Department of Chemistry, Leninskie Gory 1-3, 119991 Moscow, Russian Federation

† Electronic supplementary information (ESI) available: Procedures, compound characterization, NMR spectra. See DOI: 10.1039/x0xx00000x

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DOI: 10.1039/D4SC08561C

alkyl chlorides was performed in the presence of lithium iodide additive, which likely serves to generate more reactive alkyl iodides via nucleophilic substitution.[31] Of special note is that in all these methods, there were only a few of secondary aliphatic alkyl indium reagents have been used, which are obtained exclusively from secondary alkyl iodides, while preparation of tertiary reagents from tertiary alkyl halides is not known at all. In addition, these methods require long reaction times, which also reflects the low reducing power of indium metal. A more important aspect is that alkyl indium compounds have only been used in palladium catalyzed cross-couplings.[32,33]

Transition metal catalyzed cross-coupling reactions of organic halides with organometallic reagents have become a cornerstone of organic synthesis.[34] The modern variant of cross-coupling involves the use of metallaphotoredox conditions.[35] In particular, a dual photoredox/Ni catalytic system served as an analogue to palladium-catalyzed reactions.[36] This approach allows, on the one hand, to make the process cheaper by using the more earth abundant nickel. On the other hand, Ni/PC catalysis allows to overcome the often rate-limiting transmetallation step involving organometallic reagents by its single-electron oxidation and subsequent interception on the nickel catalyst.[37] As organometallics, trifluoroborates,[37-41] and other boron reagents[42,43] have originally been used, followed by alkyl derivatives of silicon[44-47] (Scheme 1C). Over the past few years, there has been an active search for other organometallic radical precursors. In this vein, the activation of germanium,[48,49] and zirconium reagents[50] under photoredox conditions was described. Additionally, metallaphotoredox cross-couplings with organotin compounds were also attempted and only realized in the case of very specific atrane-type alkyl tin derivatives.[51] The reagents described above are difficult to obtain directly from alkyl halides, forcing them to be obtained from more nucleophilic alkyl magnesium/zinc reagents. In addition, a number of reagents suffer from a lack of atom efficiency due to the surrounding metallic center (for silicon, tin, zirconium). The utilization of alkyl indiums could prove an effective solution to these issues. However, at present, there have been no universal methods for the synthesis of organoindium compounds from readily accessible alkyl bromides and chlorides.

Here, we overcome this problem by reacting alkyl halides with the commercially available indium(I) bromide in the presence of lithium bromide, which is more efficient than elemental indium, allowing the use of alkyl bromides and chlorides as sources for primary, secondary, and even tertiary alkyl indium reagents (Scheme 1D). We also demonstrate that the synthetic utility of alkyl indium compounds can be greatly expanded as they can undergo single-electron oxidation and serve as excellent precursors of alkyl radicals involved in the $C(sp^2)$-$C(sp^3)$ cross-coupling under metallaphotoredox conditions.

Results and discussions

Our idea is based on the fact that indium(I) bromide in donating solvents is prone to disproportionation to In(0) and In(III).[52] This combination was proposed to be effective for the following reasons. First, zero-valent metals formed as a result of reduction of their salts (such as Rieke metals) are known to be more reactive than commercial metals.[53,54] Moreover, In(I) to In(0)/In(III) conversion may have equilibrium nature,[55] thereby maintaining the surface of the metal fresh. Second, use of indium(I) bromide provides perfect stoichiometry upon conversion of RBr into $RInBr_2$. This point is expected to eliminate the formation of numerous organoindium species such as dialkyl indium(III) bromide, observed when In(0) is used. Finally, the strength of the reducing indium system may be augmented with lithium halides, which are known to be instrumental in reactions of insertion of zero-valent metals into C-X bonds,[56,57] and this was also applied for reactions using elemental indium.[58-60] Bromide anion can also break-up alkyl indium bromide aggregates to give more reactive indium-ate species.[61] In the earlier literature, examples of solvent-free interaction of indium(I) salts with simple primary alkyl halides were described,[62-64] while in coordinating systems disproportionation of indium(I) and formation of indium(II) salts were noted.[62,65]

Ethyl 4-bromobutyrate (**1a**) was selected as a model substrate, and its reaction with indium(I) bromide was evaluated, and several model alkyl halides were also tested (Table 1). The reaction of **1a** with 1.5 equivalent of InBr/LiBr combination in N,N-dimethylformamide (1.0 M of **1a**) was complete within 3 h at 80 °C leading to virtually quantitative formation reagent **2a** (entry 1). The reaction performed in deuterated solvent (d7-DMF) allowed to record ^1H and ^{13}C NMR spectra of **2a**, which showed a single organoindium species, which was assigned to monoorganoindium $RInBr_2$ based on HRMS (ESI-TOF); bis(alkyl)indium substances (such as R_2InBr) were not detected (see ESI for details). Decrease of the reaction temperature led to some decrease of the yield, while application of the ultrasound had positive effect (entries 3 and 4); performing the reaction at room temperature over 16 hours was also inefficient (entry 5). In other solvents, the reaction was slower than in DMF, though reasonable yields of **2a** can be achieved by extending the reaction time to 16 hours (entries 7-9). Use of LiCl instead of LiBr gave notable yield decrease (entry 10), likely, due to competitive substitution of bromide of **1a** by chloride resulting in formation of less reactive alkyl chloride (the alkyl chloride was detected by GC-MS analysis). In the absence of LiBr or use of metallic indium led to notably decreased yields of **2a** (entries 11 and 12). It was reported that benzyl (but not alkyl) halides react with elemental indium in the presence of air leading to hydroperoxides.[66] It was rewarding to find that in our system, when the reaction was set up in the air atmosphere, the organoindium reagent was formed in 71% yield (entry 6). Moreover, air does not decrease the concentration of **2a** in DMF-d7 over one month (stored in a vial under air, periodically checked by NMR with internal standard, see ESI for details).

Then, we evaluated secondary and tertiary alkyl bromides (Scheme 2). After brief optimization (see ESI for details) we found that for secondary acyclic and cyclic bromides, longer time (12 h) and increased loading of InBr/LiBr system (2 equiv) were needed to achieve high yields. Reagent **2b** was also characterized by ^1H and ^{13}C NMR and HRMS (ESI-TOF). In case of cyclohexyl bromide, lithium chloride could be used instead of lithium bromide because in this case S_N2 halogen exchange (cyclohexyl bromide with chloride) is slower than the formation of the organoindium **2c-Cl**. The latter protocol was applied for the preparation of the organoindium reagent from 30 mmol of cyclohexyl bromide. Preparation of *tert*-butyl indium reagent **2d** under standard conditions was hampered by its instability at temperatures above 50 °C. Fortunately, reagent

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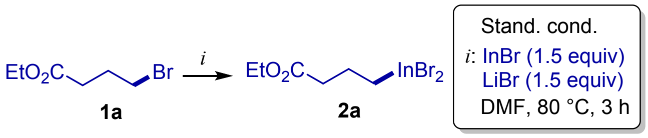
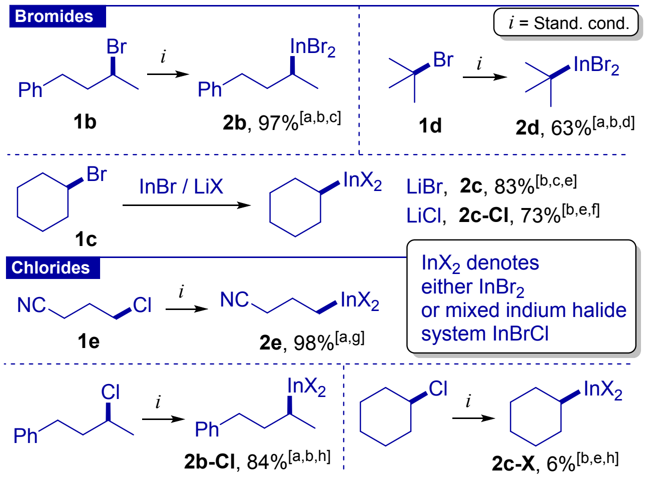
2d could be obtained at 40 °C using ultrasonication in 63% yield. This is the first example of organoidnium formation from tertiary alkyl halides through direct insertion.

Table 1. Optimization studies.



#	Deviations from stand. cond.	Y. of **2a**, %[a]
1	none	99
2	InBr/LiBr (1.2 equiv)	97
3	heat at 60 °C	80
4	50 °C + ultrasound	90
5[b]	20 °C	40
6	air atmosphere	71
7[b]	DME as solvent	95
8[b]	MeCN as solvent	77
9[b]	THF as solvent	75
10	LiCl (1.5 equiv) instead of LiBr	35
11	no LiBr	48
12	In (1.5 equiv) instead of InBr	41

[a] Determined by ^{1}H NMR with 1,3,5-trioxane as an internal standard. [b] 16 h.

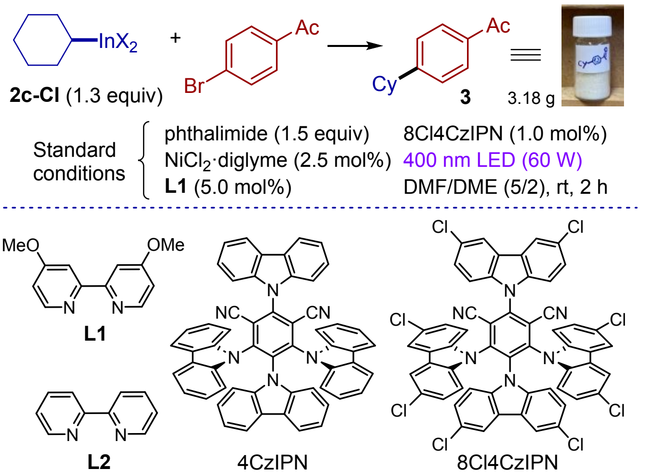


Scheme 2. Organoindium reagents. [a] Determined by ^{1}H NMR with 1,3,5-trioxane as an internal standard. [b] 12 h. [c] InBr/LiBr (2.0 equiv). [d] 40 °C/ultrasound. [e] Determined by GC-FID with tetraline as standard after iodination. [f] InBr/LiCl (2.0 equiv). [g] 6 h. [h] InBr (2.0 equiv), LiBr (3.0 equiv), 100 °C.

Alkyl chlorides are notably less reactive compared to bromides. However, primary halides can undergo halogen exchange, as was exemplified for **1a** (see discussion above and entry 10). Correspondingly, we proposed that combination of alkyl chloride with LiBr can reversibly generate alkyl bromide, which in turn can efficiently be converted into organoindium reagent.[31] Indeed, 1-chloro-3-cyanopropane gave reagent **2e** in 98% yield under standard conditions but within 6 hours. The intermediate formation of 1-bromo-3-cyanobutane was confirmed by monitoring of the reaction by GS-MS analysis. Fortunately, reagent **2b-Cl** was also obtained from the corresponding alkyl chloride in 84% yield by increasing the amount of lithium bromide to 3 equiv and performing the reaction at 100 °C for 12 hours. Cyclohexyl chloride reacted slowly, apparently, due to slow S$_N$2 halogen exchange. *tert*-Butyl chloride did not to give the indium reagent.

Organoindium reagents were evaluated as sources of radicals in C(sp^2)-C(sp^3) cross-coupling under dual photoredox/nickel catalysis. Variation of conditions for a model coupling partners (cyclohexyl indium reagent **2c-Cl** and 4-bromoacetophenone) was undertaken (Table 2). The reaction is best performed using chlorinated cyanoarene photocatalyst 8Cl4CzIPN,[67] nickel dichloride-diglyme complex and 4,4’-dimethoxybipyridine (**L1**). Slight excess of the indium reagent (1.3 equiv) was applied in a mixed solvent DMF/DME (5/2). The reaction was irradiated by 400 nm light and was complete within 2 hours furnishing target product in 91% isolated yield (entry 1). Use of stoichiometric amount of phthalimide additive was required, which is believed to play dual role: to suppress the side protodehalogenation of arylbromide and to hinder the formation of catalytically inactive low-valent oligomeric nickel complexes[68] (entry 7). While reactions were routinely carried under argon, running the experiment under air atmosphere had little effect (entry 2). To evaluate sensitivity towards moisture, cross-coupling of **2c** with 4-bromoacetophenone was performed in the presence of 4 equiv of water leading to product **3** in 90% yield (see ESI for details). The reaction did not proceed without the nickel complex or light (entries 8 and 11); without photocatalyst or ligand only traces of the product were detected (entries 9 and 10). Finally, the reaction can be easily scaled up, with the experiment on 17.5 mmol of aryl bromide affording gram quantities of the product (90%, 3.18 g, see photo).

Table 2. Optimization of the cross-coupling.



#	Deviations from stand. cond.	Y. of **3**, %[a]
1	none	92 (91)[b]
2	open to air	87
3	455 nm LED	82
4	4CzIPN as PC (455 nm LED)	80
5	without DME	76
6	**L2** as ligand	76
7	no phthalimide	64
8	no NiCl$_2$·diglyme	0
9	no **L1**	< 5
10	no PC	< 5
11	no light	0

[a] Determined by ^{1}H NMR with CH$_2$Br$_2$ as an internal standard. [b] Isolated yield.

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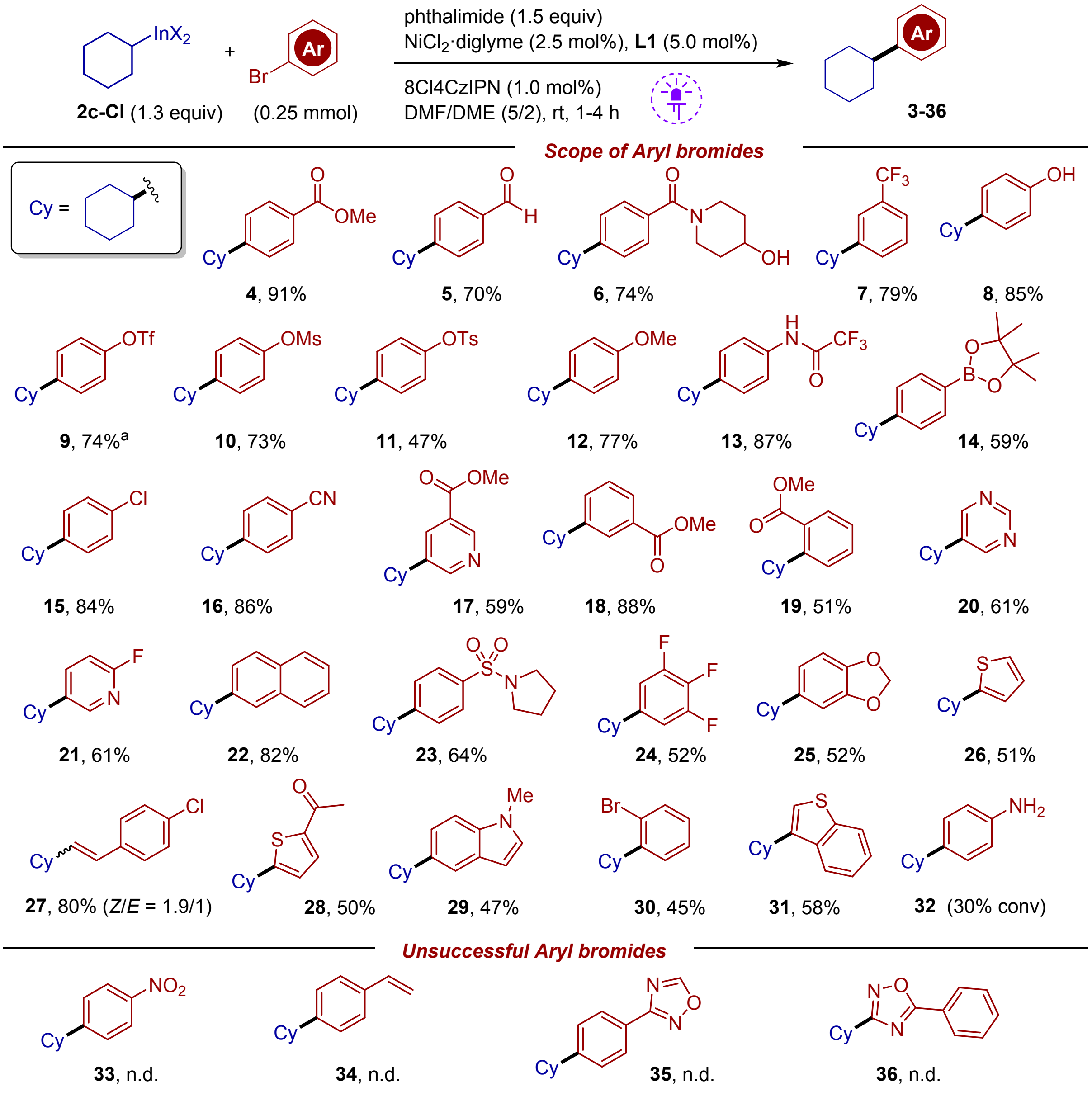
Under the optimized conditions, a scope of aryl halides was first evaluated using reagent **2c-Cl** (Scheme 3). The reaction tolerates many functional groups such as acetyl, ester, nitrile, aldehyde, amide, sulfonamide, and (pinacolato)boryl fragment. Comparison of bromides bearing ester group at *para*, *meta* and *ortho* positions suggested that *para* and *meta* substrates have similar reactivity (products **4** and **18**), while *ortho* substrate afforded product **19** in a diminished yield of 51%, which is likely associated with steric effect. Based on this observation, selective substitution of one bromine in 1,2-dibromobenzene was carried out (product **30**). Aryl bromides bearing triflate, mesylate and tosylate were coupled (products **9**-**11**) (triflate and mesylate groups can be slowly affected under our conditions in case of electron depleting arenes, see mechanistic discussion below). It should be pointed out that in palladium cross-couplings, aryl triflates are known to be more reactive compared to bromides. In a similar vein, the chlorine atom remained unaffected (product **15**) The reaction tolerates fragments with active hydrogen such as phenol (**8**) and trifluoroacetanilide (**13**). Various bromo-substituted heterocycles were evaluated. Thus, the reaction can work with derivatives of pyridine, pyrimidine, indole, thiophene and benzothiophene. 2-Fluoropyridine fragment, which is prone to fluoride substitution, withstands the reaction conditions (product **21**). A fragment of vinyl bromide was also successfully involved into cross-coupling affording a mixture of isomers in good yield (product **27**). Despite impressive functional group tolerances, several types of substrates were problematic. In particular, 4-bromoaniline showed very low reactivity, with 30% conversion after 16 hours. In reactions of 4-bromonitrobenzene and 4-bromostyrene no products were formed (see bottom of Scheme 3). Similar outcome was with oxadiazole-containing substrates, which suffered from decomposition of this fragile heterocycle; in these experiments, complete conversion of starting bromides was noted along with detection of benzonitrile by GC-MS analysis.



Scheme 3. Scope of (hetero)aryl bromide coupling partners. Isolated yields are shown.

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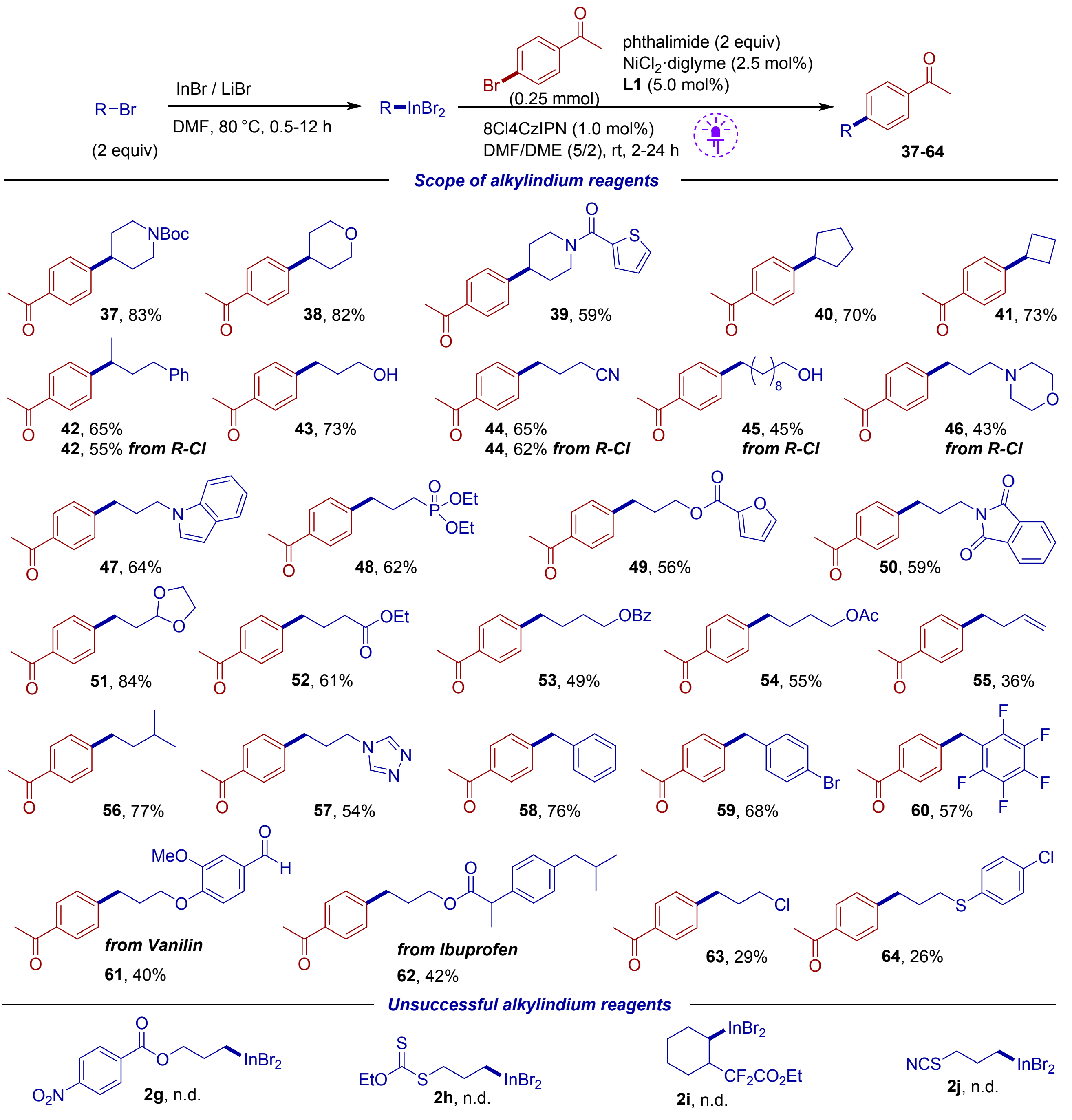
Then we focused on the variation of alkyl indium component (Scheme 4). The indium reagent was prepared from 2 equiv of alkyl bromide or chloride followed by addition of 1,2-dimethoxyethane co-solvent, aryl bromide (1 equiv) and other components. The reaction smoothly proceeded with primary and secondary alkyl indium reagents containing N-Boc protected cyclic amine, ester and cyano groups, phosphonate and dioxolane fragment, as well as unprotected hydroxy group. Various heterocycles within the indium component such as thiophene, furan, indole and triazole were tolerated. Products **42** and **44** could be obtained starting from both alkyl bromides and chlorides, though reactions from bromides gave slightly higher yields. The reaction of *tert*-butyl indium reagent was unsuccessful, which is in accord with literature reports requiring different conditions for the adoption of tertiary radicals in



Scheme 4. Scope of organoindium coupling partners. Isolated yields are shown, which are based on aryl bromide.

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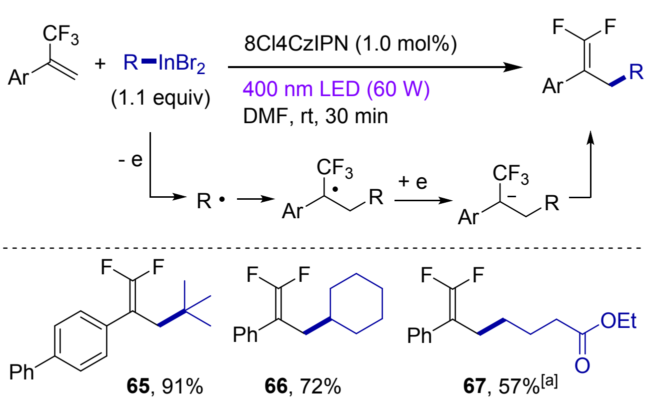
photoredox/Ni systems.[69,70] Indium reagent prepared from 4-bromobut-1-ene gave decreased yield (product **55**), likely, due to none-innocence of the terminal double bond. Moderate yield was also observed for the reaction of 1-bromo-3-chloropropane (product **63**) because of competitive Cl/Br exchange. Benzyl bromides can also be easily converted into the indium reagents under our conditions, which required only 30 min, followed by cross-coupling (products **58**-**60**). It is interesting to note that reagent derived from *para*-bromobenzyl bromide gave the coupling product **59** suggesting that the C-Br of 4-bromoacetophenone undergoes faster activation than the C-Br of the product. Several functionalized reagents could not be prepared, which is associated either with incompatibility with InBr/LiBr system (**2g**) or with rapid degradation of the indium reagent (**2h-j**) (see bottom of Scheme 4).

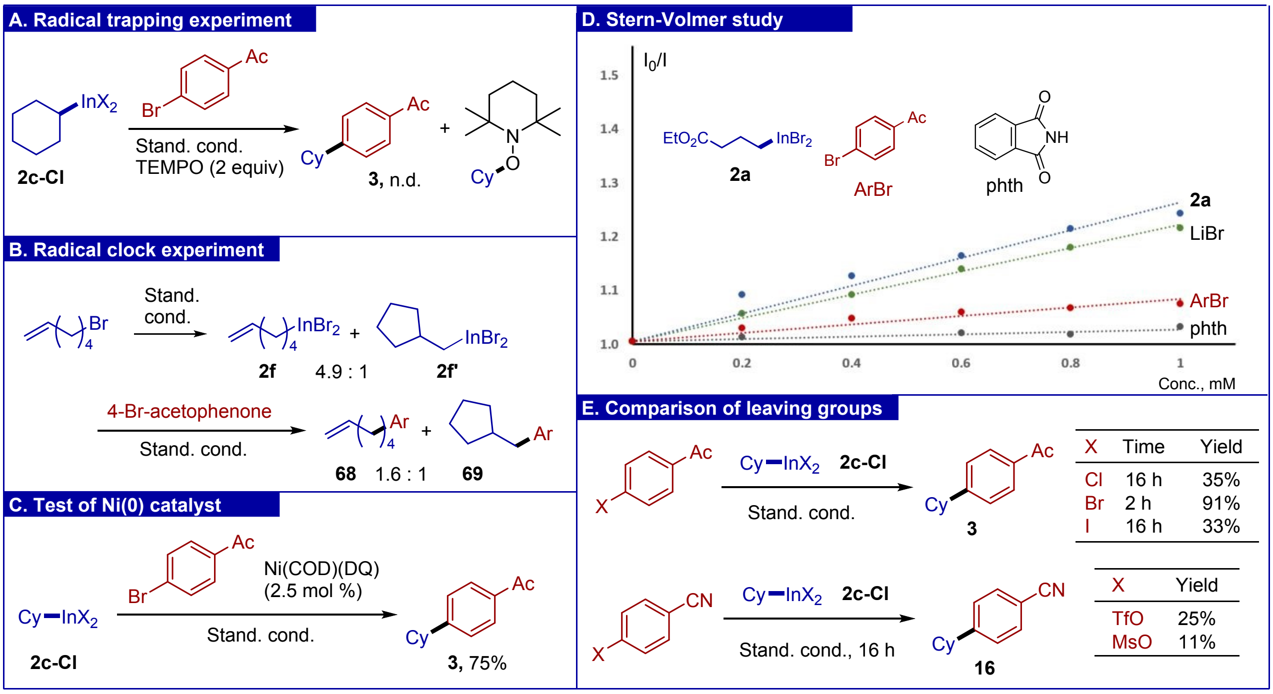
α-(Trifluoromethyl)styrenes are another class of typical radical-accepting substrates working under redox conditions.[71] Indeed, alkylindiums cannot be viewed as C-nucleophiles towards α-(trifluoromethyl)styrenes (confirmed by a blank experiment, see ESI for details). On the other hand, interaction of these styrenes with organoindiums should proceed via generation of alkyl radical (by oxidation of organoindiums), radical addition at the styrene, SET reduction and fluoride elimination (Scheme 5). The reaction of α-(trifluoromethyl)styrenes with organoindium reagents was catalyzed by 8Cl4CzIPN and, for tertiary and secondary reagents, was complete within 30 min! Here, the tertiary indium reagent was the most effective (in line with formation of the most stable tertiary radical). On the other hand, for primary alkyl group, two equivalents of the indium reagent were necessary together with a long reaction time of 16 hours.



Scheme 5. Reaction of α-(trifluoromethyl)styrenes. Isolated yields are shown. [a] 2.0 equiv of organoindium reagents was used; reaction time 16 h.

Mechanistic considerations

To get deeper insight into the reaction mechanism, several experiments were carried out. First, addition of TEMPO completely blocked the cross-coupling under standard conditions along with formation of trapping product between TEMPO and cyclohexyl radical (Scheme 6A). To perform a radical clock experiment, 1-hexen-6-yl bromide was subjected to the reaction with InBr/LiBr system, which gave a mixture of open/cyclic indium reagents (Scheme 6B). Their cross-coupling gave a mixture with increased content of the cyclic product. In the literature, a reaction of 1-hexen-6-yl bromide in a nickel photoredox cross-coupling gave 2.5/1 mixture of open/cyclic products.[72] These experiments support the radical



Scheme 6. Mechanistic experiments.

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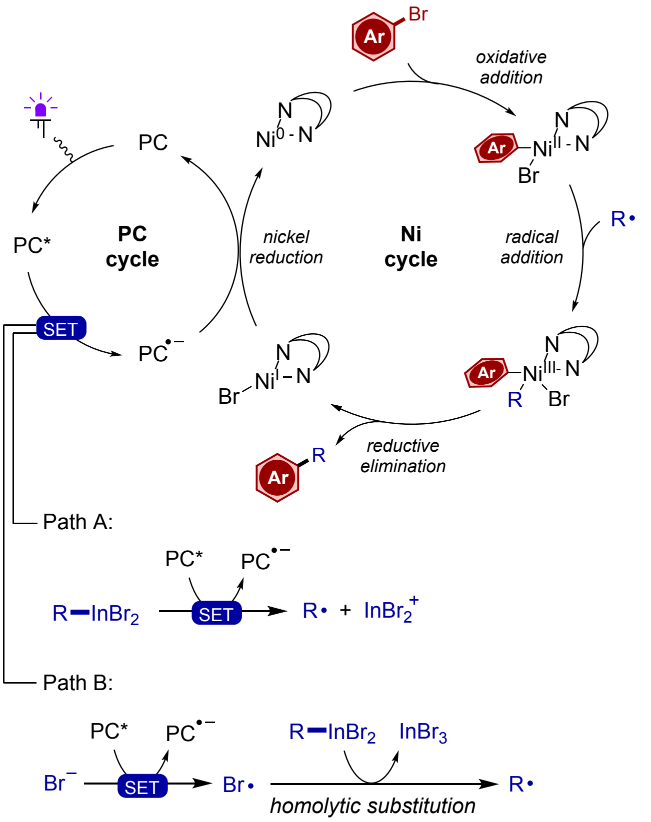
character of the cross-coupling. To support the intermediacy of low valent nickel species in the catalytic cycle, the reaction was performed using zero-valent complex Ni(COD)(DQ)[73] (DQ = duroquinone) as a source of nickel (instead of $NiCl_2$-diglyme), which gave the expected product **3** in good yield (Scheme 6C). To identify species interacting with the photocatalyst, Stern-Volmer fluorescence quenching was evaluated (Scheme 6D). It was found that there was virtually no quenching of photocatalyst excited state (PC*) with phthalimide and aryl bromide. On the other hand, lithium bromide, as well as organoindium reagent **2a** served as fluorescencequenchers. As follows from the slopes of Stern-Volmer plots, for the reagent **2a**, the quenching was most efficient. This indicates that reagent **2a** undergoes single-electron oxidation by PC*. Fluorescence quenching by solution of lithium bromide suggests possible oxidation of bromide by the photocatalyst, which is in accord with redox potentials [E (Br^-/Br) = +0.80 V vs SCE;[74] for 8Cl4CzIPN, E($PC^*/PC^{\cdot-}$) = +1.58 V vs SCE[63]). Measurement of redox potential of reagent **2a** in DMF solution by cyclic voltammetry gave potential of +0.89 V vs SCE, with the curve resembling that of bromide anion (see SI for details). The quantum yield of a standard reaction (**2c** with 4-bromoacetophenone) was determined to be 0.023. Finally, to estimate the influence of various leaving groups of the aryl component on reaction efficiency, several experiments were carried out (Scheme 6E). Thus, chloro-, bromo-, and iodo-substituted acetophenones were compared, among which the bromine derivative gave the highest yield. Whereas the low reactivity of aryl chloride was expected, the low yield and especially low conversion of aryl iodide was surprising. It can be tentatively proposed that iodide anion formed as reaction progresses can exert inhibiting effect. We noted that aryl triflate and mesylate fragments remained unaffected in reaction of 4-tryflyloxy- and 4-mesyloxy-bromobenzenes (see Scheme 3, products **9** and **10**). Correspondingly, we tested highly electron deficient triflate and mesylate derived from 4-cyanophenol. These substrates bearing the electron depleting group reacted slowly, and even after 16 hours only low yields were observed. This means that the reaction is selective for aromatic bromides thereby opening opportunities for performing orthogonal transformations.

Based on the obtained experimental data, the following mechanism can be proposed (Scheme 7). Two types of the photocatalytic cycle may be operative. Thus, organoindium reagent is oxidized by photoexcited catalyst to generate the alkyl radical (path A). Alternatively, bromide is oxidized to generate bromine radical, which in turn attacks at the indium center of organoindium to liberate the alkyl radical (path B). For the nickel cycle, the reduced state of the photocatalyst generates Ni(0) with its oxidative addition into the C-Br bond to give arylnickel(II) intermediate. Radical addition at the nickel and reductive elimination from Ni(III) completes the catalytic cycle.

Conclusions

The utilization of photoredox catalysis has enabled the exploration of novel reaction pathways for alkyl indium compounds, which serve as sources of alkyl radicals upon light promoted single electron oxidation. Organoindium reagents were incorporated into the nickel/photoredox catalyzed cross-coupling with aryl bromides, as well as in reaction with α-(trifluoromethyl)styrenes. The synthetic utility of these reactions was enhanced with the advent of a universal methodology for the synthesis of alkyl indium reagents. Both preparation of organoindium reagents and the metallaphotoredox cross-coupling are insensitive to air and moisture, and tolerate wide variety of sensitive functional groups.



Scheme 7. Proposed mechanism.

Author contributions

Investigation, A.A. Gladkov. and D.Y. Cheboksarov.; conceptualization, A.A. Gladkov. and V.V. Levin.; data curation, A.A. Gladkov. and D.Y. Cheboksarov.; writing – review & editing, A.A. Gladkov., V.V. Levin. and A.D. Dilman.

Conflicts of interest

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There are no conflicts to declare.

Data availability

Procedures, compound characterization, NMR spectra are available in the ESI.

Acknowledgements

This work was supported by the Russian Science Foundation (Project 23-13-00130).

Notes and references

1 M. Schlosser, ed., *Organometallics in Synthesis: Third Manual*, John Wiley & Sons, Hoboken, New Jersey, 2013.

2 P. Knochel, ed., Handbook of Functionalized Organometallics: Applications in Synthesis, WILEY-VCH, Weinheim, 2005.

3 K. Duan, X. Yan, Y. Liu and Z. Li, *Adv. Synth. Cat.*, 2018, **360**, 2781–2795.

4 P. Renaud, A. Beauseigneur, A. Brecht-Forster, B. Becattini, V. Darmency, S. Kandhasamy, F. Montermini, C. Ollivier, P. Panchaud, D. Pozzi, E. M. Scanlan, A.-P. Schaffner and V. Weber, *Pure Appl. Chem.*, 2007, **79**, 223–233.

5 T. Akindele, K.-i. Yamada and K. Tomioka, *Acc. Chem. Res.*, 2009, **42**, 345–355.

6 M. Kubisiak, K. Zelga, W. Bury, I. Justyniak, K. Budny-Godlewski, Z. Ochal and J. Lewiński, *Chem. Sci.*, 2015, **6**, 3102-3108.

7 A. A. Gladkov, G. N. Chernov, V. V. Levin, V. A. Kokorekin and A. D. Dilman, *Org. Lett.*, 2021, **23**, 9645–9648.

8 A. A. Gladkov, V. V. Levin and A. D. Dilman, *J. Org. Chem.*, 2023, **88**, 1260–1269.

9 A. A. Gladkov, V. V. Levin and A. D. Dilman, *Adv. Synth. Cat.*, 2023, **365**, 3387–3391.

10 A. A. Gladkov, V. V. Levin and A. D. Dilman, *J. Org. Chem.*, 2024, **89**, 11826–11835.

11 Z.-L. Shen, S.-Y. Wang, Y.-K. Chok, Y.-H. Xu and T.-P. Loh, *Chem. Rev.*, 2013, **113**, 271–401.

12 J. Burgess, *Chem. Soc. Rev.*, 1996, **25**, 85–92.

13 V. I. Supranovich, V. V. Levin and A. D. Dilman, *Org. Lett.*, 2024, **26**, 4537–4541.

14 Y.-H. Chen and P. Knochel, *Angew. Chem. Int. Ed.*, 2008, **47**, 7648–7651.

15 V. Papoian and T. Minehan, *J. Org. Chem.*, 2008, **73**, 7376–7379.

16 L. Adak and N. Yoshikai, *J. Org. Chem.*, 2011, **76**, 7563–7568.

17 A. A. Rafaniello, R. Kumar, R. C. Phillips and M. J. Gaunt, *Angew. Chem. Int. Ed.*, 2024, **63**, e202408287.

18 V. Nair, S. Ros, C. N. Jayan and B. S. Pillai, *Tetrahedron*, 2004, **60**, 1959–1982.

19 P. H. Lee and K. Lee, *Angew. Chem. Int. Ed.*, 2005, **44**, 3253–3256.

20 S. A. Babu, M. Yasuda, I. Shibata and A. Baba, *J. Org. Chem.*, 2005, **70**, 10408–10419.

21 S. A. Babu, M. Yasuda, I. Shibata and A. Baba, *J. Org. Chem.*, 2005, **70**, 10408–10419.

22 H. C. Clark and A. L. Pickard, *J. Organomet. Chem.*, 1967, **8**, 427–434.

23 I. Pérez, J. P. Sestelo and L. A. Sarandeses, *J. Am. Chem. Soc.*, 2001, **123**, 4155–4160.

24 Z.-L. Shen, K. K. K. Goh, Y.-S. Yang, Y.-C. Lai, C. H. A. Wong, H.-L. Cheong and T.-P. Loh, *Angew. Chem. Int. Ed.*, 2011, **50**, 511–514.

25 P. Wang, B.-Z. Chen, Y.-C. Guo, W. Rao, Z.-L. Shen, *Tetrahedron Lett.* **2019**, *60*, 151288.

26 Y. Yu, Y. Feng, W. Ma, H. Li, M. Yang, G. Zhang, Y. Yang, *ChemistrySelect* **2022**, *7*, e202202061.

27 P. Wang, X.-D. Song, B.-Z. Chen, W. Rao, Z.-L. Shen, *Catal. Commun.* **2019**, *132*, 105824.

28 X.-X. Feng, Z. Wu, Q.-D. Wang, B.-Z. Chen, W. Rao, J.-M. Yang, Z.-L. Shen, *Appl. Organomet. Chem.* **2019**, *33*, e5110.

29 B.-Z. Chen, C.-X. Wang, Z.-H. Jing, X.-Q. Chu, T.-P. Loh, Z.-L. Shen, *Org. Chem. Front.* **2019**, *6*, 313–318.

30 M.-L. Zhi, B.-Z. Chen, W. Deng, X.-Q. Chu, T.-P. Loh, Z.-L. Shen, *J. Org. Chem.* **2019**, *84*, 3017–3023.

31 B.-Z. Chen, M.-L. Zhi, C.-X. Wang, X.-Q. Chu, Z.-L. Shen, T.-P. Loh, *Org. Lett.* **2018**, *20*, 1902–1905.

32 K. Zhao, L. Shen, Z.-L. Shen, T.-P. Loh, *Chem. Soc. Rev.* **2017**, *46*, 586–602.

33 M. M. Martínez, J. Pérez Sestelo, L. A. Sarandeses, in *Adv. Organomet. Chem., Vol. 80* (Ed.: P. J. Pérez), Academic Press, **2023**, pp. 177–253.

34 C. C. C. Johansson Seechurn, M. O. Kitching, T. J. Colacot, V. Snieckus, *Angew. Chem. Int. Ed.* **2012**, *51*, 5062–5085.

35 A. Y. Chan, I. B. Perry, N. B. Bissonnette, B. F. Buksh, G. A. Edwards, L. I. Frye, O. L. Garry, M. N. Lavagnino, B. X. Li, Y. Liang, E. Mao, A. Millet, J. V. Oakley, N. L. Reed, H. A. Sakai, C. P. Seath and D. W. C. MacMillan, *Chem. Rev.*, 2022, **122**, 1485–1542.

36 V. M. Chernyshev and V. P. Ananikov, *ACS Catal.*, 2022, **12**, 1180–1200.

37 J. C. Tellis, D. N. Primer, G. A. Molander, *Science* **2014**, *345*, 433–436.

38 J. C. Tellis, C. B. Kelly, D. N. Primer, M. Jouffroy, N. R. Patel, G. A. Molander, *Acc. Chem. Res.* **2016**, *49*, 1429–1439.

39 J. K. Matsui, Á. Gutiérrez-Bonet, M. Rotella, R. Alam, O. Gutierrez, G. A. Molander, *Angew. Chem. Int. Ed.* **2018**, *57*, 15847–15851.

40 M. W. Campbell, J. S. Compton, C. B. Kelly, G. A. Molander, *J. Am. Chem. Soc.* **2019**, *141*, 20069–20078.

41 J. P. Phelan, S. B. Lang, J. Sim, S. Berritt, A. J. Peat, K. Billings, L. Fan, G. A. Molander, *J. Am. Chem. Soc.* **2019**, *141*, 3723–3732.

42 T. Wan, L. Capaldo, J. Djossou, A. Staffa, F. J. de Zwart, B. de Bruin, T. Noël, *Nat. Commun.* **2024**, *15*, 4028.

43 M. Oliva, S. Pillitteri, J. Schörgenhumer, R. Saito, E. V. Van der Eycken, U. K. Sharma, *Chem. Sci.* **2024**, DOI: 10.1039/D1034SC04196H.

44 V. Corcé, L.-M. Chamoreau, E. Derat, J.-P. Goddard, C. Ollivier, L. Fensterbank, *Angew. Chem. Int. Ed.* **2015**, *54*, 11414–11418.

45 M. Jouffroy, D. N. Primer, G. A. Molander, *J. Am. Chem. Soc.* **2016**, *138*, 475–478.

46 C. Lévêque, L. Chenneberg, V. Corcé, J.-P. Goddard, C. Ollivier, L. Fensterbank, *Org. Chem. Front.* **2016**, *3*, 462–465.

47 B. A. Vara, M. Jouffroy, G. A. Molander, *Chem. Sci.* **2017**, *8*, 530–535.

48 Q.-H. Xu, L.-P. Wei, B. Xiao, *Angew. Chem. Int. Ed.* **2022**, *61*, e202115592.

49 A. Selmani, M. D. Schoetz, A. E. Queen, F. Schoenebeck, *ACS Catal.* **2022**, *12*, 4833–4839.

50 Y. Gao, C. Yang, S. Bai, X. Liu, Q. Wu, J. Wang, C. Jiang, X. Qi, *Chem* **2020**, *6*, 675-688.

51 Z. Zhou, J. Yang, B. Yang, Y. Han, L. Zhu, X.-S. Xue, F. Zhu, *Angew. Chem. Int. Ed.* **2023**, *62*, e202314832.

View Article Online
DOI: 10.1039/D4SC08521C

52 J. A. J. Pardoe, A. J. Downs, *Chem. Rev.* **2007**, *107*, 2–45.
53 A. Fürstner, *Angew. Chem. Int. Ed.* **1993**, *32*, 164–189.
54 L. A. Garza-Rodríguez, B. I. Kharisov, O. V. Kharissova, *Synth. React. Inorg. Met. Org. Chem.* **2009**, *39*, 270–290.
55 G. Biedermann, T. Wallin, *Acta Chem. Scand.* **1960**, *14*, 594–608.
56 A. Krasovskiy, V. Malakhov, A. Gavryushin, P. Knochel, *Angew. Chem. Int. Ed.* **2006**, *45*, 6040–6044.
57 C. Feng, D. W. Cunningham, Q. T. Easter, S. A. Blum, *J. Am. Chem. Soc.* **2016**, *138*, 11156–11159.
58 Y.-H. Chen, P. Knochel, *Angew. Chem. Int. Ed.* **2008**, *47*, 7648–7651.
59 Y.-H. Chen, M. Sun, P. Knochel, *Angew. Chem. Int. Ed.* **2009**, *48*, 2236–2239.
60 V. Papoian, T. Minehan, *J. Org. Chem.* **2008**, *73*, 7376–7379.
61 J. J. Habeeb, F. F. Said, D. G. Tuck, *J. Organomet. Chem.* **1980**, *190*, 325–334.
62 L. G. Waterworth, I. J. Worrall, *J. Organomet. Chem.* **1974**, *81*, 23–26.
63 J. S. Poland, D. G. Tuck, *J. Organomet. Chem.* **1972**, *42*, 315–323.
64 L. Waterworth, I. J. Worrall, *J. Chem. Soc. D* **1971**, 569–569.
65 C. Peppe, D. G. Tuck, L. Victoriano, *J. Chem. Soc., Dalton Trans.* **1982**, 2165–2168.
66 Y. Hou, J. Hu, R. Xu, S. Pan, X. Zeng, G. Zhong, *Org. Lett.* **2019**, *21*, 4428–4432.
67 F. Le Vaillant, M. Garreau, S. Nicolai, G. Gryn'ova, C. Corminboeuf, J. Waser, *Chem. Sci.* **2018**, *9*, 5883–5889.
68 C. N. Prieto Kullmer, J. A. Kautzky, S. W. Krska, T. Nowak, S. D. Dreher, D. W. C. MacMillan, *Science* **2022**, *376*, 532–539.
69 G. Laudadio, P. Neigenfind, Á. Péter, C. Z. Rubel, M. A. Emmanuel, M. S. Oderinde, T. E.-H. Ewing, M. D. Palkowitz, J. L. Sloane, K. W. Gillman, D. Ridge, M. D. Mandler, P. N. Bolduc, M. C. Nicastri, B. Zhang, S. Clementson, N. N. Petersen, P. Martín-Gago, P. Mykhailiuk, K. M. Engle, P. S. Baran, *Angew. Chem. Int. Ed.* **2024**, *63*, e202314617.
70 D. N. Primer, G. A. Molander, *J. Am. Chem. Soc.* **2017**, *139*, 9847–9850.
71 F. Tian, G. Yan, J. Yu, *Chem. Commun.* **2019**, *55*, 13486–13505.
72 A. Luridiana, D. Mazzarella, L. Capaldo, J. A. Rincón, P. García-Losada, C. Mateos, M. O. Frederick, M. Nuño, W. Jan Buma, T. Noël, *ACS Catal.* **2022**, *12*, 11216–11225.
73 V. T. Tran, Z.-Q. Li, O. Apolinar, J. Derosa, M. V. Joannou, S. R. Wisniewski, M. D. Eastgate, K. M. Engle, *Angew. Chem. Int. Ed.* **2020**, *59*, 7409–7413.
74 S. K. Kariofillis, S. Jiang, A. M. Żurański, S. S. Gandhi, J. I. Martinez Alvarado, A. G. Doyle, *J. Am. Chem. Soc.* **2022**, *144*, 1045–1055.

The data supporting this article have been included as part of the Supplementary Information.

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DOI: 10.1039/D4SC08521C