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Hypervalent organoiodine compounds: from reagents to valuable building blocks in synthesis

Gwendal Grelier, Benjamin Darses and Philippe Dauban*

Abstract
Most of the polyvalent organoiodine compounds derive from iodoarenes, which are released in stoichiometric amounts in any reaction mediated by $\lambda^3$- or $\lambda^5$-iodanes. In parallel to the development of solid-supported reagents or reactions catalytic in iodine, a third strategy has emerged to address this issue in terms of sustainability. The atom-economy of transformations involving stoichiometric amounts of $\lambda^3$- or $\lambda^5$-iodanes, thus, has been improved by designing tandem reactions that allows for incorporating the aryl motif into the products through a subsequent one-pot nucleophilic addition or catalytic coupling reaction. This review summarizes the main achievements reported in this area.

Introduction
Synthetic applications of the hypervalent iodine chemistry have grown exponentially in the last four decades as highlighted by several books and comprehensive reviews dedicated to this topic [1-13]. A still growing number of $\lambda^3$- and $\lambda^5$-iodanes are now available as non-toxic and environmentally benign reagents that allow for performing a wide range of transformations under mild conditions. The oxidation of functional groups, halogenations, C–C, C–O, or C–N couplings, dearomatization of phenols, rearrangements, to name but a few, have been reported using these compounds thereby reflecting their versatility.

A survey of the general structure of polyvalent organoiodine compounds reveals that they are prepared mostly from iodoarene starting materials. Accordingly, any transformation relying on stoichiometric amounts of these reagents will inevitably produce the same quantity of iodoarene derivatives, which can be considered as a waste in the context of sustainable chemistry. Various strategies, thus, have been described to address this issue. A first solution has arisen from the development of polystyrene-supported reagents, which allows their recycling following simple filtration and re-oxidation (reaction 1 in Scheme 1a) [14,15]. More recently, the design of
processes catalytic in iodine compounds has been extensively investigated and significant achievements have been reported making iodine compounds now useful organocatalysts in asymmetric synthesis (reaction 2 in Scheme 1a) [15-24].

In parallel to these investigations, a third strategy has been envisaged with the development of tandem reactions involving a step that enables the introduction of the iodoarene side-compound into the products. Various sequences combining oxidation reactions, nucleophilic additions, or aromatic couplings, thus, have been reported (Scheme 1b). In addition to address the issue of sustainability, this complementary solution has provided opportunities to explore a new chemical space. This review aims to highlight the main achievements reported in this context since the first study described in 1995 on the palladium-catalyzed cross couplings of symmetrical diphenyl-\(\lambda^3\)-iodanes with sodium tetraphenylborate [25].

Review

Tandem additions

\(\lambda^5\)-iodanes such as the Dess–Martin periodinane or IBX [26], and \(\lambda^3\)-iodanes such as benziodoxolones [27], are versatile reagents in organic synthesis. These are often used, respectively, for the oxidation of alcohols or carbonyl compounds, and in atom-transfer reactions. These transformations always lead to the release of 2-iodobenzoic acid in the reaction mixture. Thus, with the aim to value this side product, a variety of tandem reactions including an oxidation and an addition step have been designed to incorporate the nucleophilic acid into the final product.

\(\lambda^5\)-Iodane reagents

One of the first studies documenting the use of the iodoarene moiety as a building block in synthesis has been reported in 2004. The \(\lambda^5\)-iodane reagent IBX has been shown to promote the \(\alpha\)-functionalization of ketones following the introduction of the 2-iodobenzoic acid motif (Scheme 2a) [28].

Mono- and disubstituted products 1 and 2 are obtained respectively from aliphatic ketones and methyl aryl ketones. The reaction conditions have then been extended to the functionalization of alkenes to afford 1,2-halo-oxygenated compounds 3 (Scheme 2b) [29]. This transformation has recently been used for the stereoselective \(\text{trans}\) iodo-benzylation of glycosals using a combination of IBX and molecular iodine, that is considered as a source of I\(^{+}\) formed from the in situ generated hypoiodite species [30].

The controlled oxidation of various \(N\)-(alkyl)- and \(N\)-(aryl)pyrroles with Dess–Martin periodinane also leads to...
introduction of the iodobenzoic acid motif onto the pyrrole ring. 5-Aroyloxy-γ-lactams 4 can be isolated with yields in the 56–96% range, however, the reaction requires 2.5 equivalents of the λ5-iodane reagent, a result that supports its limited efficiency in terms of atom economy (Scheme 3) [31].

The group of Szabó has first reported the use of copper(I) iodide as a catalyst for the regioselective difunctionalization of aromatic alkynes and alkenes with an optimal atom-economy (Scheme 4a) [34,35]. The transformation proceeds efficiently, particularly in the presence of an electron-donating substituent

\[ \text{Scheme 4: Catalytic benzoyloxy-trifluoromethylation reported by Szabó.} \]

**λ3-Iodane reagents: CF₃-benziodoxolone (Togni’s reagent)**

The ability to introduce the 2-iodobenzoic acid motif released from benziodoxolones has first been noticed by Ochiai in an isolated example of radical benzoylation of THF [32], and by Gouverneur in the study of trifluoromethylation of allylsilanes [33]. The use of this acid as an oxygen nucleophile, then, has been more fully investigated by the groups of Szabó and Sodeoka who have simultaneously described the copper-catalyzed benzoyloxy-trifluoromethylation of alkenes and alkynes using Togni’s reagent 5.

\[ \text{Scheme 3: Functionalization of pyrroles with DMP.} \]

**Scheme 3:** Functionalization of ketones and alkenes with IBX.

\[ \text{Scheme 2: Functionalization of ketones and alkenes with IBX.} \]
on the aromatic ring. The same reaction has been later found to be mediated by copper(I) cyanide starting from p-methoxy-styrene [36]. However, under these conditions, other styrene derivatives bearing a phenyl, a tert-butyl, or an electron-withdrawing substituent have been shown to afford products resulting from a cyanotrifluoromethylation reaction.

The mechanistic study of the oxy-trifluoromethylation of phenylacetylene has then led to demonstrate that the reaction is accelerated in the presence of additives such as B$_2$pin$_2$ [35]. A mechanism involving an initial step of transmetallation of B$_2$pin$_2$ with the Cu(I) catalyst was proposed (Scheme 4b). The intermediate Cu–Bpin, then, could undergo an oxidative addition into the CF$_3$–I bond to give 8 that, after a CF$_3$ radical transfer, would afford the radicals 9 and 10. Radical recombination followed by reductive elimination would finally lead to the E-product and regenerate the Cu–Bpin complex.

The group of Sodeoka, in parallel, has described the same 1,2-difunctionalization reaction of alkenes and alkynes with 5 in the presence of [Cu(MeCN)$_4$]PF$_6$ as the catalyst (Scheme 5a) [37]. It should be pointed out that this copper(I) complex was previously described by Szabó as a poor catalyst in his process. The reaction applies to phenylacetylenes and various types of aromatic alkenes, however, its scope has been extended to dienes and disubstituted styrenes by using the less Lewis acidic Cu$_2$I complex (Scheme 5b) [38]. Interestingly, cis and trans β-methyl-styrenes lead to product 14 with the same syn:anti ratio while 1,4-addition products containing an (E)-olefin are selectively obtained from dienes. The authors have also shown that the reaction performed in the presence of a stoichiometric amount of p-TsOH gives β-trifluoromethylstyrene derivatives instead of the expected oxy-trifluoromethyl compound.

The benzoyloxy-trifluoromethylation of dienes has also been reported with CuCN as the catalyst. The reaction, again, is selective with respect to the olefin geometry – (E)-alkenes are exclusively obtained – and the regioselectivity – products resulting from a sterically-controlled 1,4-anti-addition are selectively isolated (Scheme 6) [39]. The proposed radical mechanism, which takes into account the beneficial effect of the bulky monophosphine P(t-Bu)$_3$ on the reaction rate, is consistent with that reported by Szabó (Scheme 4b).

The scope of the copper-catalyzed benzoyloxy-trifluoromethylation has been extended to several other substrates. Starting from N-(aryl)- and N-(benzyl)allylamines 16, the reaction affords β-benzoyloxy-β′-trifluoromethylamines 17 through the formation of an aziridine intermediate (Scheme 7) [40]. The latter was further utilized to give access to a variety of β-trifluo-

**Scheme 5:** Catalytic benzoyloxy-trifluoromethylation reported by Mideoka.
romethylamines after reaction with several O-, N-, S-, and C-nucleophiles.

Application of the same reaction conditions to enynes 18 has led to the discovery of an elegant cascade that gives access to a wide range of trifluoromethylated five-membered carbo- and heterocycles 19 (Scheme 8) [41]. Six-membered heterocycles can also be obtained in good yields. The reaction is believed to involve either a tertiary radical intermediate or a carbocationic species, both being able to undergo a 5-exo-dig type cyclization to afford compounds 19.

The copper-catalyzed benzoyloxy-trifluoromethylation has also been applied to the conversion of allenes 20. A regioselective 1,2-addition on the internal π-bond was observed to afford the products 21, because of the presence of a heteroatom substituent that can stabilize the radical or cationic intermediate by coordination with the copper complex (Scheme 9) [42]. However, the efficiency of the reaction is limited by the need to use 2 equivalents of allenes 20 to obtain good yields.
*Iodane reagents: alkynylbenziodoxolone*

Ethynylbenziodoxolone (EBX) is a powerful reagent to perform the electrophilic alkynylation of various functional groups such as carbonyl derivatives, thiols, arenes and heteroarenes [43,44]. A first solution to value the 2-iodobenzoic moiety released from EBX has arisen from the reaction of derivatives 22 with *N*-(aryl)imines 23 in the presence of 10 mol % of Pd(OAc)$_2$, which gives access to tri- or tetrasubstituted furans 24 and *N*-(aryl)formamides 25 (Scheme 10a) [45]. The scope of the overall transformation is wide both in terms of imines and EBX reagents.

![Scheme 10: Alkynylation of *N*-(aryl)imines with EBX for the formation of furans.](image)

The group of Waser has discovered an atom-economical multi-component process between alkynylbenziodoxolones 22 and diazo compounds, which is catalyzed by the copper(I) complex [Cu(MeCN)$_4$]BF$_4$. The reaction gives access to versatile building blocks while generating only N$_2$ as side-product (Scheme 11a) [46]. Worth of mention is the use of a 1,2-diamine ligand 34 that is crucial to obtain good conversions.

Compounds 31 resulting from the *gem*-addition of the benzoate motif and the alkynyl group are obtained from various acceptor or donor–acceptor diazo compounds 30, while the use of vinyl-diazio derivatives 32 leads to enynes 33 arising from the vinyllogous addition of the carboxylate. Significantly, the benzoyloxy-alkynylation reaction can be applied to the late-stage modification of complex products such as steroids. On the other hand, both the alkyne and the iodoarene moiety can be modified through post-transformation reactions thereby increasing the molecular diversity accessible with this process. The mechanism of the reaction (Scheme 11b) would first involve the formation of the copper-carbene species 35, to which the carboxylate of alkynylbenziodoxolone could add to afford the intermediate 36. Final alkyne transfer would give rise to the products 31 and 33, however, the nature of this alkynylation step remains to be elucidated.

In a subsequent study, the same group has demonstrated the ability to perform the reaction with TIPS-EBX 37 in an enantioselective manner using the cyclopropylbisoaxolone ligand 38 (Scheme 12) [47]. Starting from various acceptor diazo compounds, the *gem*-addition of the carboxylate and the alkyne proceeds with ees of up to 98% to afford α-benzoyloxy propargylic derivatives 39. Again the strategy can be applied to the late-stage modification of steroids with high levels of diastereo-selectivity.

**Iodane reagents: azidobenziodoxolone (ABX) and chlorobenziodoxolone**

In a similar manner to the previously described catalytic benzyloxy-trifluoromethylation using Togni’s reagent 5 (Scheme 4 and Scheme 5), the 1,2-benzoyloxy-azidation of alkenes can be performed in the presence of a copper catalyst with the
Scheme 11: Catalytic benzoyloxy-alkynylation of diazo compounds

Scheme 12: Catalytic asymmetric benzoyloxy-alkynylation of diazo compounds.

Scheme 13: Catalytic 1,2-benzoyloxy-azidation of alkenes.

Scheme 14: Catalytic 1,2-benzoyloxy-azidation of enamides.

azidobenziodoxolone ABX 40. The reaction takes place in dichloromethane using the copper(II) complex Cu(OTf)₂ as the catalyst thereby leading to the expected products 41 with yields in the 26–75% range (Scheme 13) [48]. Interestingly, an alkene diazidation reaction is observed by simply performing the transformation in DMSO and replacing Cu(OTf)₂ by CuI as the catalyst.

Enamides 42 are also relevant substrates for the 1,2-benzoyloxy-azidation reaction. Based on a preliminary observation made during their study on catalytic trifluoromethylation of enamides [49], the group of Gillaizeau has reported the catalytic conversion of enamides with various ABX derivatives 44.
The group of Hamashima has reported that various 1,2-difunctionalizations of alkenes can occur with chlorobenziodoxolone 45 [51]. Oxychlorinated, dichlorinated, azidochlorinated and chlorothiocyanated products can thus be isolated mostly from styrenyl substrates. However, the treatment of 45 with tetra-

butylammonium iodide followed by the addition of an alkene leads to the formation of products 46 resulting from a 1,2-

benzoyloxyiodination and isolated with moderate to excellent yields (Scheme 15). The reaction is believed to take place through the formation of a hypoidous species that activates the olefin via an iodonium intermediate.

Scheme 15: Catalytic 1,2-benzoyloxy-iodination of alkenes.

Tandem catalytic couplings

Diaryliodonium compounds, also named diaryl-\(\lambda^3\)-iodanes, are stable, easy-to-handle crystalline solids, which have found numerous applications as arylating agents since their first use in the \(\alpha\)-phenylation of 1,3-diones reported in the 60s [52-54]. Because of the hypernucleofuge nature of the Ar–I moiety in \(\lambda^3\)-iodanes, their reactivity is higher than that of the corresponding aryl halides, a property that has been widely exploited to develop efficient transition-metal-catalyzed cross coupling reactions [55]. The latter, however, allow for transferring only one of the two aromatic motifs of the iodonium reagents. Several elegant catalytic domino reactions, accordingly, have been recently designed to incorporate both aryl groups into the products.

Cyclic diaryl-\(\lambda^3\)-iodanes

Cyclic diaryl-\(\lambda^3\)-iodanes have been extensively studied for the preparation of complex polycyclic structures following the application of catalytic domino reactions. The group of Hayashi has reported in 2004 the first example of the transformation of a cyclic diaryl-\(\lambda^3\)-iodane, for which both Ar–I bonds are used in a palladium cross-coupling reaction [56]. It relies on a double Heck reaction performed with methyl vinyl ketone in the presence of Pd(OAc)\(_2\) in THF, and affords the dibenzoalylidenefluorene 47 in an excellent 88% yield (Scheme 16).

Scheme 16: Seminal study with cyclic diaryl-\(\lambda^3\)-iodane.

Ten years later, Huang, Wen and co-workers have demonstrated that, in the presence of both a terminal alkylene and a boronic acid, various cyclic diaryl-\(\lambda^3\)-iodanes undergo a transition-metal catalyzed cascade reaction to afford alkylidenefluorenes 49 (Scheme 17) [57]. In terms of mechanism, a Pd(0)/Cu(I)-catalyzed Sonogashira coupling reaction from the iodonium salt 48 delivers a 2-alkynyl-2′-iodoarene 50 that, then, cyclizes to 51 via insertion of the Pd(0) species into the iodoarene moiety and migratory addition into the proximal alkylene. Transmetalation of the vinylpalladium with the boronic acid and reductive elimination finally leads to alkylidenefluorenes 49. This multicomponent strategy allows the variation of the alkylene, the boronic acid and the diaryliodonium salts, but the use of non-symmetrical diaryl-\(\lambda^3\)-iodanes raises the issue of regioselectivity.

This strategy has been then extended to the preparation of alkylene-substituted alkylidenefluorenes 53 by replacing the arylboronic acid with a second equivalent of the terminal alkylene and performing the reaction at 35 °C (Scheme 18) [58]. Importantly, the reaction with non-symmetrical diaryl-\(\lambda^3\)-iodanes gives the corresponding products with high regioselectivities, when an \(o\)-methyl substituent is present on one aromatic ring. The reaction can also be performed sequentially with the isolation of the iodoaryl intermediate, which can be resubmitted to the cyclization conditions in the presence of a different terminal alkylene, or an activated alkene.

The same authors have then showed that the reaction of cyclic diaryl-\(\lambda^3\)-iodanes in the presence of internal alkynes and the catalytic system Pd(OAc)\(_2\)-PCy\(_3\) affords functionalized phenanthrenes 54 in moderate to good yields (Scheme 19) [59]. Indoles also are relevant substrates for the tandem arylation with cyclic diaryl-\(\lambda^3\)-iodanes, allowing the preparation of dibenzocarbazoles 55 in moderate yields (Scheme 20) [60]. The reaction is catalyzed simply by Pd(OAc)\(_2\) in the absence of any ligands, and tolerates a variety of substituents on both the indole and the iodonium salt. However, the atom-economy of the reac-
Scheme 17: Synthesis of alkylidenefluorenes from cyclic diaryl-λ^3^-iodanes.

Scheme 18: Synthesis of alkyne-substituted alkylidenefluorenes.

Scheme 19: Synthesis of phenanthrenes from cyclic diaryl-λ^3^-iodanes.

Another multicomponent reaction has been designed for the preparation of triazolophenanthridines 56 that are obtained in a one-pot manner by combination of a cyclic diaryl-λ^3^-iodane with sodium azide and a terminal alkyne, in the presence of 10 mol % of Cul (Scheme 21) [61]. The expected triazolophenanthridines were generally isolated in good to excellent yields, but the presence of strong electron-donating or withdrawing groups on the phenylacetylene moiety proved to be detrimental to the conversion. In addition, mixtures of regioisomeric products are generally obtained starting from non-symmetrical diaryl-λ^3^-iodanes. A series of reactions has been performed to gain insight into the mechanism that first involves the formation of a 2'-iodobiphenyl-2-azide promoted by the copper complex. The latter then catalyzes an intermolecular [3 + 2] cycloaddition with the alkyne. Finally, the copper-triazole moiety inserts intramolecularly into the second Ar–I bond, allowing a ring closure after reductive elimination.

Starting from the ortho-N-(acyl)diaryl-λ^3^-iodanes 57, a combination of copper and palladium catalysis, in the presence of a phosphine ligand, induces the internal O arylation of the proximal amide moiety, followed by a subsequent metal-catalyzed coupling-reaction with the resulting Ar–I motif (Scheme 22)
The group of Zhang has developed a one-pot procedure for the sequential difunctionalization of cyclic diaryl-$\lambda^3$-iodanes (Scheme 23) [63]. The first step relies on the copper-catalyzed coupling between an anthranilic acid derivative and the biphenyl moiety. The resulting iodoarene product is then submitted to a Sonogashira coupling reaction, allowing the one-pot preparation of a library of biphenyl products 59 in moderate to good yields. Nevertheless, a two-fold excess of the iodonium triflate is needed to secure a good conversion, a point that limits again the atom-economy of the overall process.

Similarly, the group of Liu has described the double Suzuki–Miyaura coupling reaction of cyclic diaryl-$\lambda^3$-iodanes with various aryl- and heteroarylboronic acids for the formation of $\alpha$-tetraaryls 60 (Scheme 24) [64]. The reaction generally requires only 1 mol % of Pd(dbta)$_2$ to afford the expected products in good to high yields. It is worth mentioning that a comparative test starting from a 2,2'-diiodobiaryl has led to a much higher yield of 95%.
lower yield when compared to that obtained from the corresponding diaryl-λ³-iodane.

In 2011, the group of Detert has reported the first example of a palladium-catalyzed double C–N bond formation starting from the cyclic (phenyl)(pyrido)-λ³-iodane \(61\) (Scheme 25) [65]. The reaction requires the use of 4 mol % of \(\text{Pd}_2\)(dba)_3, 12 mol % of Xantphos, 2.8 equivalents of Cs_2CO_3 and 1.2 equivalents of benzylamine to afford the corresponding δ-carboline in a 65% yield.

Two years later, the group of Nachtsheim has designed a similar strategy for the preparation of \(N\)-(aryl)carbazoles \(61\) from cyclic diaryl-λ³-iodanes (Scheme 26) [66]. The palladium phosphine ligand plays a crucial role as a bidentate ligand with a bite angle greater than 100° such as DPEphos (104°) or Xantphos (108°) significantly improves the yields. The reaction applies to a series of anilines and aliphatic amines, but electron-poor anilines afford better results than their electron-rich congeners, while a hindered amine (\(t\)-BuNH_2) completely inhibits the reaction.

Shortly after, a similar synthesis of carbazoles involving Cu(OAc)_2 as the catalyst in the presence of ethylene glycol both as a ligand and the co-solvent has been reported (Scheme 27) [67]. A variety of amines such as anilines, sulfonamides and aliphatic amines has been utilized though in large excess. But in contrast to the previous method, electron-rich anilines proved to be better candidates for this reaction than the electron-poor analogs.

The group of Jiang has very recently described a complementary method for the synthesis of carbazoles by combining cyclic diaryl-λ³-iodanes with sodium azide in the presence of copper(I) thiophene-2-carboxylate (CuTc) and triphenylphosphine. The reaction affords the expected of N–H free derivatives \(63\) in moderate to high yields, irrespective of the nature of the substituents (Scheme 28) [68]. The scope of the reaction has been extended to 6-membered ring cyclic diaryl-λ³-iodanes \(64\). The acridines \(65\), hence, have been obtained with similar yields.

The group of Shimizu has reported the formation of dibenzo-thiophenes \(66\) following the reaction of cyclic diaryl-λ³-iodanes.
with potassium thioacetate as the sulfur donor, and CuCl$_2$ as the catalyst (Scheme 29) [69]. The reaction can be performed either in THF or DMSO, affording both symmetrical and non-symmetrical products in good to excellent yields.

A similar approach involving the N-benzylthiocarbamate-triethylamine salt as the sulfur source and copper sulfate as the catalyst also provides dibenzothiophenes isolated generally in good to excellent yields, irrespective of the nature of the substituents (Scheme 31) [71]. The transformation has been extended to other cyclic diaryl-$\lambda^3$-iodanes by using 2,2'-bipyridine as the copper ligand, allowing the preparation of the corresponding thioxanthenes, phenoxythiones and dibenzothiepinines in moderate to good yields.

The scope of the reaction has been extended by using a combination of 10 mol % of Cu(OTf)$_2$, 12 mol % of 1,10-phenanthroline, and 2 equivalents of potassium phosphate, as reported by the group of Jiang (Scheme 30) [70]. Six- to eight-membered sulfur heterocycles can thus be isolated from cyclic diaryl-$\lambda^3$-iodanes. More significantly, the reaction can be applied to acyclic diaryl-$\lambda^3$-iodanes (vide infra).

The same group has then developed a radical method to access the corresponding sulfones from cyclic diaryl-$\lambda^3$-iodanes (Scheme 33) [73]. The reaction is catalyzed by a 1,10-phenanthroline-copper complex and affords the dibenzothiophene-5,5-dioxides in moderate to high yields. The transformation has been further extended to the synthesis of a new series of molecules, where the central thiophene moiety is replaced by a 6-membered heterocycle, which is substituted by a gem-dimethyl or a cyclopropyl group. In this case, the reaction can be performed under metal-free conditions in the presence of a catalytic amount of dimethylthlyenediamine.
Linear diaryl-λ^3^-iodanes

When compared to cyclic diaryl-λ^3^-iodanes, the linear analogues inherently raise a more challenging issue to address in terms of sustainability, particularly in the case of non-symmetrical reagents. As mentioned in the introduction, the first study documenting the coupling of both aromatic groups of a diaryl-λ^3^-iodane has been reported in 1995 by Bumagin and co-workers [25]. One equivalent of symmetrical diaryl-λ^3^-iodanes could be engaged in palladium-catalyzed cross-coupling reactions with 0.55 equivalent of sodium tetraphenylborate to afford 2 equivalents of the corresponding biphenyl products in nearly quantitative yields (Scheme 34). It is assumed that the first cross coupling reaction with the iodonium salt liberates an aryl iodide moiety, available for the second palladium-catalyzed coupling reaction.

Three years later, the high yielding N-arylation of 1H-1,2,3-benzotriazole (BTA), utilizing symmetrical diaryl-λ^3^-iodanes as two-fold aryl donors has been reported in the presence of Pd(OAc)₂ and TPPTS as a water-soluble ligand, and copper(II) phenylcyclopropylcarboxylate (Scheme 35) [74]. Noteworthy, it is mentioned that Ar–I fails to furnish the N-arylation products.
under the same reaction conditions, leading the authors to conclude that this suggested intermediate remains in the coordination sphere of the palladium catalyst.

In 2015, the group of Greaney has described a tandem copper-catalyzed C\textsubscript{3}–H/N–H arylation of indoles with diaryl-λ\textsuperscript{3}-iodanes (Scheme 36) [75]. The reaction first involves the use of 20 mol % of CuI and 1.1 equivalents of di-tert-butylpyridine (dtbpy) to convert the indole to the C\textsubscript{3}–H arylated product. The released Ar–I building block, then, can be engaged in the subsequent step of N–H arylation by adding 30 mol % of dimethyl-ethylenediamine (DMEDA) and potassium phosphate to the same pot. Symmetrical diaryl-λ\textsuperscript{3}-iodanes afford the diarylated indoles 80 with yields ranging from 41% to 67%. More significantly, whereas non-symmetrical diaryl-λ\textsuperscript{3}-iodanes based on electron poor/rich aryl moieties do not provide good levels of regiocontrol in the tandem process, the use of (aryl)(dimethyluracyl)-λ\textsuperscript{3}-iodanes allows for obtaining difunctionalized indoles of type 81 resulting from the regioselective introduction of the dimethyluracyl group at the N–H position.

The same group has then reported a remarkable domino process for the introduction of both aromatic rings of diaryl-λ\textsuperscript{3}-iodanes, though a small excess of this reagent is needed to obtain good yields. An initial N-arylation reaction of 3,5-dimethylpyrazole is performed in the presence of potassium carbonate, in xylene at 70 °C, releasing 1 equivalent of aryl iodide. The latter is then used for a sequential ruthenium-catalyzed ortho-C–H functionalization directed by the pyrazole group (Scheme 37) [76]. Starting from non-symmetrical diaryl-λ\textsuperscript{3}-iodanes, the electron-poorer or more sterically hindered aromatic group is first transferred to the 3,5-dimethylpyrazole. The reaction has been extended to 1,2,3-triazoles, benzotriazole, and pyrazole. In the latter case, the use of (styril)(aryl)-λ\textsuperscript{3}-iodanes has also proved to be possible, with the styril moiety being selectively transferred in the first step. The following step of C–H activation
then gives access to 2,2-diarylated enamines \(83\) isolated as a single isomer with respect to the alkene geometry.

While the diarylation of anilines with cyclic diaryl-\(\lambda^3\)-iodanes for the formation of \(N\)-arylated carbazoles has been described in 2013 [66,67], the truly intermolecular diarylation of anilines with linear reagents has been described only in 2017 by the group Greaney [77]. Except for anilines bearing strong electron-withdrawing substituents (\(p\)-NO\(_2\)), the triarylated amines \(84\) can be obtained in moderate to good yields, irrespective of the substitution of the aniline and the diaryl-\(\lambda^3\)-iodane (Scheme 38). However, the scope of the reaction is limited to symmetrical diaryl-\(\lambda^3\)-iodanes as non-symmetrical reagents afford mixtures of \(N\)-arylated products in the first step of the tandem process.

Alternative to diaryl-\(\lambda^3\)-iodanes for the \(\alpha\)-arylation of carbonyl compounds

In addition to their role as aryl donors in numerous metal-catalyzed couplings, diaryl-\(\lambda^3\)-iodanes are also relevant reagents to perform the \(\alpha\)-arylation of enolates. However, the reaction is again limited to the transfer of a single aryl group. As an alternative to address this issue of atom-economy, the group Shafir has reported the metal- and base-free arylation of ketones and cyanoketones using \([\text{bis(trifluoroacetoxy)iodo}]\)arenes \(\text{ArI(OCOCF}_3\text{)}\) (Scheme 39) [78]. The reaction can also be applied to cyclic 1,3-diones with equal efficiency [79].

As mentioned in the Scheme 30, the group of Jiang has reported the formation of cyclic diarylsulfides from the corresponding cyclic diaryl-\(\lambda^3\)-iodanes, utilizing potassium thio-acetate as the sulfur source, in the presence of 10 mol % of Cu(OTf)₂, and 12 mol % of 1,10-phenanthroline [70]. This transformation has been successfully applied to linear diaryl-\(\lambda^3\)-iodanes (Scheme 39). Interestingly, symmetrical and non-symmetrical reagents bearing two electronically different aryl groups can be transferred to provide the corresponding diarylsulfide products \(85\), a result that stands in contrast to the observation made by Greaney in his study with anilines described in Scheme 38.

Mechanistic studies supported by DFT calculation have led to propose that the rate-determining step of the process would be the ligand exchange between TFA and the \(O\)-enolate (Scheme 41) [79]. The resulting cationic intermediate \(88\) could rapidly evolve through a \([3,3]\) rearrangement. Even though the \(C\)-enolate \(89\) is more stable than its \(O\)-tautomer \(88\), the rearrangement step seems to be much faster. The use of the radical scavenger TEMPO had no effect on the reaction outcome suggesting that the initial hypothesis is correct. By screening additives, it was shown that the hypervalent iodine could be quickly generated in situ by using Oxone as a terminal oxidant, thereby allowing for extending the scope of the reaction in terms of iodoarenes.

Tandem oxidation–catalytic couplings

A large range of oxidation reactions can be performed with \([\text{bis(acyloxy)iodo}]\)arenes best represented by the commercially available reagents PhI(OAc)₂ and PhI(OCOR-Bu)₂. These \(\lambda^3\)-iodanes have been widely used in atom-transfer reactions, particularly for the generation of metal-bound nitrenes that are highly active species for the aziridination of alkenes and the direct amination of benzylic, allylic or tertiary C(sp\(^3\))–H bonds.
Seminal catalytic nitrene transfers mediated by $\lambda^3$-iodanes [86-89] were described from iminoiodinanes of general formula PhI=NR that can be prepared mainly from sulfonamides [90]. However, the scope of catalytic C(sp$^3$)–H amination and alkene aziridination reactions has been greatly enhanced following the discovery of practical procedures for the in situ generation of iminoiodinanes, a synthesis which is known to be troublesome [91-93]. According to these protocols and following the design of dirhodium(II) complexes, highly efficient catalytic nitrene transfers have been reported from carbamates [92], sulfamates [94-97], ureas and guanidines [98], sulfamides [99], hydroxylamine-derived sulfamates [100], carbamimidates [101], and sulfonimidamides [102-107]. These reactions involve the formation of a metal-bound nitrene that can insert into a C(sp$^3$)–H bond or a $\pi$-bond via the asynchronous concerted addition of a singlet species or a stepwise radical pathway (Scheme 42) [83,84].

While these transformations cannot be performed under conditions catalytic in iodine, recent investigations have revealed the possibility to value the iodoarene side-product in a subsequent one-pot palladium-catalyzed cross-coupling reaction. The use of a sulfonimidamide (S*NH$_2$) as a chiral nitrene precursor, in combination with the chiral dirhodium(II) complex Rh$_2$(S-nta)$_4$ has led to the discovery of intermolecular C(sp$^3$)–H amination reactions that proceed from hydrocarbons used as the limiting components, with nearly quantitative yields and complete diastereoselectivity [102-105]. Such a highly efficient atom-transfer process has provided the opportunity to design a tandem of C–N and C–C bond-forming reactions that relies on an initial step of catalytic nitrene addition. The latter would release the iodoarene that could be coupled to a suitable functionality previously introduced on the starting material. The strategy has been first validated from TMS-protected alkyne derivatives via a tandem of C(sp$^3$)–H amination/sila-Sonogashira–Hagihara coupling (Scheme 43) [108].

The overall process affords complex nitrogen-containing compounds 92 with very good yields and complete stereocontrol starting from benzylic, allylic and adamantyl substrates. In addition, the preparation of substituted [bis(acyloxy)iodo]arenes following the reaction of iodoarenes with sodium perborate.
enables the introduction of various aryl groups on the alkyne moiety.

However, as a limitation of this study, the reaction allows for recycling at best 1 equivalent of the iodoarene while it involves the use of 1.4 equivalents of the λ3-iiodane. Moreover, it requires the design of specific alkynyl substrates that reduces its scope. With the aim to address these issues, it has been demonstrated that, in addition to its role of oxidant and coupling partner, the λ3-iiodane can simultaneously be used as the substrate for the C(sp3)-H amination reaction (Scheme 44) [109]. The catalytic auto-amination, thus, gives access to various iodoaminated intermediates that can be subsequently engaged in palladium-catalyzed Suzuki–Miyaura, Sonogashira, or Mizoroki–Heck cross-coupling reactions. Various aryl, alkenyl, or alkynyl substituents can thus be introduced in good to very good yields.

When compared to the previous strategy, not only this process enables to increase the molecular diversity, but it also displays a higher atom-efficiency as only 1.1 equivalents of the λ3-iiodane are required to achieve good to excellent conversions. In addition, it should be pointed out that the tandem reactions based on the auto-amination process enables to address the issue of chemoselectivity in some cases. For example, the Suzuki–Miyaura coupling allows for introducing a pyridinyl or a furyl ring that are not compatible with the rhodium-catalyzed oxidizing amination reactions.

In a similar manner, the group of Namitharan has very recently demonstrated that a one-pot palladium-catalyzed Heck coupling allows for transferring the aryl group of (diacetoxyiodo)arenes released after a metal-free methylenation reaction (Scheme 45) [110]. The latter that is performed by reacting PhI(OAc)2 with DMSO, applies to amidines 97 to afford the methylene intermediates 98 The following coupling leads to 1,2-diarylated acrylamidines 99 in good yields, but only starting from iodoarenes substituted by electron-donating groups.

Conclusion
With the aim to reduce the formation of iodo-containing side-products, the design of tandem reactions that enable the incor-
tandem auto-C(sp³)–H amination
Suzuki–Miyaura coupling with Ar²BMIIDA reagents

93 – 13 examples
yields 57–87%
dr 90:10 to >98:2

tandem auto-C(sp³)–H amination
Sonogashira coupling

95 – 12 examples
yields 43–88%
dr 90:10 to >98:2

tandem auto-C(sp³)–H amination
Suzuki–Miyaura coupling with alkenyl-BF₃K reagents

94 – 4 examples
yields 46–84%
dr >98:2

tandem auto-C(sp³)–H amination
Mizozuki–Heck coupling

96 - 5 examples
yields 56–72%
dr >98:2

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