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EDGE ARTICLE

General Palladium-Catalyzed Cross Coupling of Cyclopropenyl Esters

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

DOI: 10.1039/x0xx00000x

We report a method for the direct palladium-catalyzed cross coupling reactions of cyclopropenyl esters bearing a variety of substitution patterns with Csp² iodides. This reaction is largely insensitive to the electronic nature of the coupling partner. Tetramethylammonium acetate, a halide sequestrant, was exceptionally effective as an organic base. An observed KIE of 2.5 revealed C–H bond cleavage to be involved in the turnover-limiting step. This method enables the rapid assembly of cyclopropenes whose preparation previously required the use of toxic tin and arsenic reagents.

Our group has developed and utilized cyclopropene carbometallation reactions as the basis for various synthetic methods.^{1,2} These applications necessitate modular methods to synthesize cyclopropenyl esters with fully substituted olefins in high yields. Generally, Stille coupling has been used to prepare these substrates,^{3,4,5} but the required trialkyltin reagents and arsine ligands are highly toxic and Stille couplings of certain cyclopropenyl esters are sluggish and low-yielding.^{2b,c} An ideal cross coupling of cyclopropenyl esters would proceed directly via formal C–H functionalization, obviating the use of toxic tin reagents and decreasing the synthetic step count. It is also essential that such a reaction would have high functional group tolerance.

The cyclopropene ring, with ~54 kcal/mol of strain energy,⁶ is primed to undergo numerous chemical reactions involving π bond breakage. Outside of synthetic methods developed by our group⁷ and others,^{8,9} cyclopropenes are commonly used as intermediates in total synthesis,¹⁰ monomers in polymer chemistry,¹¹ and precursors to vinylcarbene intermediates.¹² In nature, cyclopropenes occur in certain toxic fatty acids.¹³

A direct Pd-catalyzed cross coupling of cyclopropenyl esters was reported by Gevorgyan in 2005 (Scheme 1a).¹⁴ This excellent method enables the arylation of trisubstituted cyclopropenes bearing aryl substituents in moderate to high yields. However, an alkyl-substituted substrate underwent the reaction in only 47% yield, and the use of starting materials bearing fewer than three ring substituents was not reported. A series of mechanistic experiments indicated that the reaction likely proceeds via coordination of the cyclopropene to a palladium species to form complex **1**, which bears carbocationic character,



Scheme 1 Relevant background and introduction to this research.

up to 92% vield

R¹ = aryl, CO₂Me R² = alkyl, aryl

and a fast deprotonation leads to a cyclopropenylpalladium species that can go on to afford the cross-coupling product. Substrates bearing alkyl substituents (R²), which do not stabilize positive charge as effectively as aryl substituents, would therefore not undergo the reaction as efficiently.

In 2019, Hashmi reported a Ag/Au-cocatalyzed alkynylation of cyclopropenes which proceeds via Ag-mediated C–H activation (Scheme 1b).¹⁵ A similar catalytic system was recently used by Waser to synthesize cyclopropene heterodimers.¹⁶ These powerful methodologies were used to synthesize a wide array

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⁺ Electronic Supplementary Information (ESI) available. See

DOI: 10.1039/x0xx00000x

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Scheme 2 Reported conditions do not effect the direct arylation of cyclopropene **2a**.

of privileged products, but *gem*-diester-containing cyclopropenes are required for high yields, and electronwithdrawing olefinic substituents are not tolerated. Cyclopropene alkynylation, as well as allylation, were also demonstrated by Xie using a dinuclear gold catalyst.¹⁷

If cyclopropenes are considered to be analogous to alkynes (based on hybridization¹⁸ and reactivity), utilizing Ag-mediated C–H activation to activate cyclopropenes for Pd-catalyzed cross coupling would be analogous to Ag-promoted formal Sonogashira couplings. Mori reported that reactions resembling the Sonogashira coupling can be promoted in high yield by either Ag₂O or ionic bases like TBAF (Scheme 1c),¹⁹ and Pale reported similar reactions with cocatalytic silver halides.²⁰

Based on this precedent, we have succeeded in developing a general, direct cross-coupling of di- and trisubstituted cyclopropenyl esters with aryl and styrenyl iodides (Scheme 1d). Disubstituted cyclopropenyl ester **2a**, prepared by Rh-catalyzed cyclopropenation,²¹ was identified as an ideal model substrate due to challenges previously encountered with the derivatization of this substrate by stannylation and Stille coupling. We first subjected **2a** to Gevorgyan's direct cross coupling conditions with PhI¹⁴ but observed only a trace of the desired product **3a** with nonspecific decomposition of the starting material (Scheme 2).

We then set out to identify reaction conditions that would effect the cross coupling of cyclopropene **2a** with PhI (Table 1). **Table 1** Optimization of reaction conditions.

CO.E

Based on the hypothesis that silver-mediated $C_{\nabla}H_{w}$ activation								
could enable a Sonogashira-type mechanism, <code>D_theo3Ag1</code>								
cocatalyzed conditions demonstrated by Pale for alkyne								
coupling were tested (entries 1-2), but desired product 3a was								
not detected. ²⁰ However, employing stoichiometric AgOAc as a								
base afforded 39% of the desired product (entry 3). Switching								
to $Ag_2O\text{-}mediated$ conditions based on those reported by Mori								
led to a high yield of $\textbf{3a}$ in just 2 hours at 70 °C (entry 4). The								
reaction proceeded slowly at ambient temperature (entry 5).								
Based on the precedent of Mori, we envisioned that a base-								
mediated reaction should be possible and would obviate the								
use of (super)stoichiometric silver. While several bases tested								
did promote formation of 3a (entries 6–8), these reactions were								
sluggish and proceeded with poor mass recovery. We therefore								
hypothesized that Ag is necessary to promote cross coupling by								
iodide abstraction from a Pd intermediate. $^{\rm 22}$ An alternative								
halide sequestrant could obviate the use of stoichiometric								
silver. While most candidates (i.e. Pb and Tl salts) present a								
safety and environmental hazard, Larrosa demonstrated the								
use of tetramethylammonium acetate as an iodide sequestrant								
in Pd-catalyzed C–H activation, $^{\rm 23}$ and a related application has								
since been explored on a process scale. ²⁴								

Conducting the arylation of **2a** with Me₄NOAc as the base in the presence of AgI led to a promising level of conversion and high mass recovery (entry 9). In the higher boiling and green solvent EtOAc, reaction at 90 °C afforded complete conversion of **2a** and 85% yield in 17 h (entry 10). Me₄NOAc was confirmed to be uniquely effective (entry 11), and furthermore, AgI does not play a catalytic role (entry 12). Indeed, a control experiment (see SI) revealed that Ag₂O does not independently effect C–H activation of cyclopropene **2a**. The reaction proceeded with a decreased catalyst loading, albeit in diminished yield (entry 13).

CO.F

Pd(PPh ₃) ₄ , PhI, base solvent, temperature, time									
			2a		3a				
Entry	Catalyst Loading	Base	Additive	Solvent	Temperature	Time	% SM	% Yield	
1	14.5 mol %	DIPEA	AgI (29 mol %)	DMF	23 °C	17 h	n.d.		
2	14.5 mol %	DIPEA	AgI (29 mol %)	THF	70 °C	17 h	n.d.		
3	7.2 mol %	AgOAc		THF	70 °C	18 h		39%	
4	7.2 mol %	Ag_2O		THF	70 °C	2 h		84%	
5	7.2 mol %	Ag_2O		THF	23 °C	18 h	51%	28%	
6	7.2 mol %	TBAF		THF	70 °C	21 h	42%	22%	
7	7.2 mol %	KOPh		THF	70 °C	16 h	20%	33%	
8	7.2 mol %	CsOAc		THF	70 °C	17 h	23%	20%	
9	7.2 mol %	Me ₄ NOAc	AgI (29 mol %)	THF	70 °C	16 h	19%	68%	
10	5.7 mol %	Me ₄ NOAc	AgI (29 mol %)	EtOAc	90 °C	17 h		85%	
11	5.7 mol %	TBAOAc	AgI (29 mol %)	EtOAc	90 °C	17 h		51%	
12	5.7 mol %	Me ₄ NOAc		EtOAc	90 °C	19 h		86%	
13	1.1 mol %	Me ₄ NOAc		EtOAc	90 °C	15 h		77%	

Reactions were conducted on a 0.2–0.3 mmol scale and yields were determined by ¹H NMR analysis using 1,3,5-trimethoxybenzene as an internal standard.

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Scheme 3 Substrate scope. All reactions were conducted on a 0.5 mmol scale at 0.25 M concentration unless otherwise noted. "Conducted at 0.1 M concentration in THF at 50 °C for 20 h using 1 equiv Ag_2O instead of Me_4NOAc .

However, upon encountering reproducibility problems at lower catalyst loadings, we opted to explore the substrate scope using 5% Pd.

A variety of aryl iodides were suitable for cross-coupling with cyclopropene **2a** in moderate to high yields (Scheme 3). Phenyl product **3a** was prepared on a 1.9 g (10 mmol) scale without a significant drop in yield. Products bearing electron-donating **(3b, 3i)** and electron-withdrawing substituents **(3c, 3h)** could be furnished, and an aryl bromide **(3d)** did not interfere with the reaction, demonstrating high chemoselectivity toward aryl iodides. 2-lodothiophene and an iodoindole were also suitable coupling partners **(3e, 3f)**. Notably, ortho-iodoanisole provided product **3g** in high yield despite potential steric clash.



Scheme 4 Kinetic isotope effect experiment.

Cyclopropene starting materials bearing a variety of substitution patterns were competent substrates in this reaction. An enantioenriched trisubstituted cyclopropene prepared by the method of Davies afforded optically active product 3j.25 A p-bromophenyl group was tolerated in a similar substrate (3k). Remarkably, cyclopropenes bearing gem-diester moieties (31, 3m) underwent the cross-coupling smoothly without ring fragmentation.²⁶ Similarly, fully substituted cyclopropenes with methyl-substituted guaternary centers (3n, 30) were obtained in high yields. The reaction is also relatively insensitive to the nature of the olefinic substituent. A tethered silyloxy group (3p) and alkyl chloride (3q) were tolerated, albeit with some loss of yield to side reactions. Secondary and tertiary alkyl-substituted products were formed in moderate to high yields (3r, 3s).

This method was also applied to the alkenylation of cyclopropenes. However, in this case, milder reaction conditions were necessary due to product instability. Ag₂O-mediated conditions derived from those evaluated during the initial reaction optimization (Table 1, entry 4) provided diene products **3t** and **3u** in 77% and 71% yields, respectively. For substrates and electrophiles that did not undergo the desired reaction, see the supporting information.

To interrogate the mechanism of this cross-coupling, the deuterium kinetic isotope effect for the reaction was measured by preparing deuterated cyclopropene **2a-D** and conducting two reactions in parallel (Scheme 4). A primary KIE ($k_{H}/k_{D} = 2.5$) was observed, indicating that C–H bond cleavage occurs in the turnover-limiting step of the reaction.²⁷ This is in contrast to the related reaction studied by Gevorgyan,¹⁴ which exhibited a k_{H}/k_{D} value of 1.0.

On the basis of this result and literature precedent, we propose



Scheme 5 Proposed catalytic cycle.

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Scheme 6 Utility of products reported herein.

a catalytic cycle for the reported reaction (Scheme 5). An anionic Pd(0) species **4** would engage in oxidative addition with aryl iodide to provide Pd(II) acetate complex **5**, following iodide sequestration. The latter complex could coordinate to a cyclopropene **2**, leading to complex **6**. Then, turnover-limiting deprotonation would afford cyclopropenyl complex **7**, which could undergo reductive elimination to release product **3** and complete the catalytic cycle.

Solutions of Pd(PPh₃)₄ containing acetate have been shown to transiently form anionic complex **4**, which is responsible for oxidative addition.²⁸ Amatore found that ligand substitution of iodide with acetate is neccessary for PhPdI(PPh₃)₂ to react with styrene via migratory insertion. While in the present case migratory insertion does not occur, as evidenced by the lack of formation of Heck-type methylenecyclopropane products when R¹ = alkyl, iodide sequestration is likely necessary to favor formation of acetate complex **5** and enable coordination of **2** to the palladium center.

The subsequent step, deprotonation of the substrate and formation of cyclopropenyl palladium species **7**, is turnoverlimiting as evidenced by the observed KIE. While we cannot definitively rule out an intramolecular concerted metallationdeprotonation (CMD) mechanism involving a palladiumcoordinated acetate ligand, the competence of fluoride and phenoxide bases (see Table 1, entries 6, 7) and the lack of a significant rate acceleration in the presence of acetate suggest an intermolecular deprotonation event akin to the step proposed by Gevorgyan¹⁴ or similar processes in Cu-free Sonogashira-type couplings.²⁹

The products generated by the method reported herein possess synthetic utility. For example, hydrogenation of cyclopropene **3g** over Pd/C afforded all-*cis* cyclopropane **8**. Cu-Catalyzed diastereoselective carbometallation^{2c} of cyclopropene **3n** yielded pentasubstituted cyclopropane **9** with excellent diastereoselectivity. Anisole derivative **3h** was recently advanced to cyclobutane **10** via the formation of a bicyclo[1.1.0]butane intermediate.^{2b}

Conclusions

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A method for the direct cross-coupling of cyclopropenyl esters was developed, enabled by the use of tetramethylammonium acetate as a halide sequestrant. This method is suitable for the arylation of cyclopropenyl esters bearing a variety of substitution patterns, and alkenylation was demonstrated under silver-mediated conditions. This reaction provides an improved method for the synthesis of a variety of strained synthetic building blocks.

Author contributions

Z.P.S. conceived of the project, performed experiments, analyzed data, and wrote the manuscript. I.M. supervised the project, obtained funding, and edited the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

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

Acknowledgements

This project received funding from the Israel Science Foundation administrated by the Israel Academy of Sciences and Humanities (Grant No. 1625/22). Z.P.S. gratefully acknowledges the Azrieli Foundation and Fulbright Israel for postdoctoral fellowships.

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