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Dichotomous mechanistic behavior in Narasaka-Heck cyclizations: electron rich Pd-catalysts generate iminyl radicals†

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Pd-catalyzed cyclizations of oxime esters with pendant alkenes are subject to an unusual ligand controlled mechanistic divergence. Pd-systems modified with electron deficient phosphines (e.g. P(3,5-(CF₃)₂C₆H₃)₃) promote efficient aza-Heck cyclization, wherein C-N bond formation occurs via alkene imino-palladation. Conversely, electron rich ligands, such as $P(t-Bu)_3$, cause deviation to a SET pathway and, in these cases, C-N bond formation occurs via cyclization of an iminyl radical. A series of mechanistic experiments differentiate the two pathways and the scope of the hybrid organometallic radical cyclization is outlined. This study represents a rare example in Pd-catalysis where selection between dichotomous mechanistic manifolds is facilitated solely by choice of phosphine ligand.

Introduction

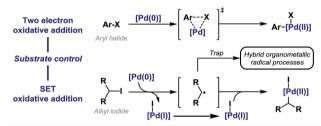
Palladium-catalyzed processes are fundamental to organic synthesis, and it is estimated that one in five C-C bond formations employed in commercial syntheses of new drugs are reliant on this technology.1 Significant and continuing efforts are focused on the development of diverse phosphine ligands to enhance key mechanistic steps, such as oxidative addition.2 Consequently, the overall efficiency of a given process is strongly dependent on the exact choice of P-based ligand. However, cases where this choice causes deviation from common two electron redox processes to one electron, radicalbased pathways are rare.3 This is despite the well documented, but underappreciated propensity of Pd(0)-systems to undergo single electron transfer (SET) oxidative addition in certain contexts,4 and the emergence of a series of hybrid organometallic-radical methodologies that invoke the intermediacy of Pd(1)-complexes (Scheme 1A).5

We have reported a range of aza-Heck methodologies that involve oxidative addition of Pd(0)-catalysts into the N-O bond of O-pentafluorobenzoyl oxime esters 1 (Scheme 1B, two electron pathway).6-8 Addition of the resulting imino-Pd intermediate 2a across a pendant alkene leads to aza-Heck (3)6,7 or cascade products.8 For these processes, electron deficient ligand systems, especially $P(3,5-(CF_3)_2C_6H_3)_3$, are most effective, they enhance migratory insertion and

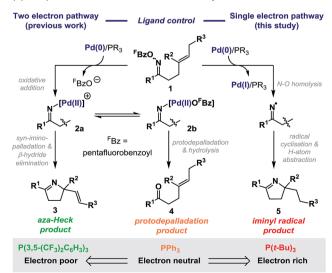
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protodepalladation of 2a/b; this latter pathway leads to the corresponding ketone 4 and predominates with electron neutral ligand systems, such as PPh₃.7 In this report we disclose that

(A) Substrate controlled mechanism selection in Pd-catalysis:



(B) Phosphine controlled mechanism selection in cyclizations of oxime esters:



Scheme 1

[†] Electronic supplementary information (ESI) available: Experimental procedures and characterisation data for all compounds are provided. CCDC 1429194. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c5sc04037j

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electron rich phosphines (e.g. $P(t-Bu)_3$) do not lead to Heck type products, but instead promote exclusive access to radical manifolds (Scheme 1B, single electron pathway). This has important implications for processes reliant upon the oxidative addition of Pd(0)-catalysts into oxime ester N-O bonds. Indeed, in addition to aza-Heck reactions, 6,7 this catalysis platform has enabled diverse methodologies, including alkene 1,2-carboaminations,8 aryl C-H aminations,9 alkene aziridinations,10 alkene 1,2-iodoaminations,11 benzyne 1,2-aminofunctionalizations,12 and C-C bond activations.13 Furthermore, this study provides convenient and unique access to iminyl radical chemistry,14 and in broader terms, represents a rare example in Pd-catalysis where selection between dichotomous mechanistic manifolds is facilitated solely by choice of phosphine ligand.3

Results and discussion

Under optimized aza-Heck conditions, which use P(3,5-(CF₃)₂C₆H₃)₃ as ligand, cyclization of O-pentafluorobenzoyl oxime ester 1a to alkene 3a occurs in 93% yield (Table 1, entry 3).7^a The *O*-pentafluorobenzoyl group is important, as, following oxidative addition, the pentafluorobenzoate leaving group undergoes facile protodecarboxylation to C₆F₅H, which drives access to cationic intermediate 2a, as required for cyclization.8 When PPh3 was used as ligand, a 30% yield of 3a was achieved (entry 1) and the mass balance consisted predominantly of the corresponding ketone, which likely arises via protodepalladation of intermediate 2b. For O-pivaloyl oxime ester 1b, cyclization to 3a was not observed using either P(3,5-(CF₃)₂C₆H₃)₃ or PPh₃, and, in both cases, the only identifiable

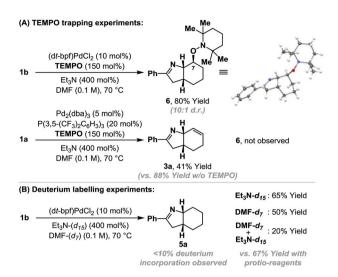
product was the corresponding ketone. Here, the issue is likely that the pivalate leaving group does not dissociate readily after oxidative addition to provide access to key cationic intermediate 2a. Thus, effective aza-Heck cyclization requires both an Opentafluorobenzoyl oxime ester and an electron deficient phosphine ligand, whereas protodepalladation predominates using electron neutral phosphines and/or weakly dissociating leaving groups. Exposure of either 1a or 1b to the electron rich Pd-system (dt-bpf)PdCl2 did not lead to aza-Heck product 3a or significant quantities of ketone. Instead, adduct 5a was isolated in 72% yield in both cases (entries 4 and 5). 5a is a formal 'reductive' aza-Heck product, however, as outlined later, this likely arises via a Pd(0)-triggered radical-based cyclization. The situation appears to be general for a range of electron rich phosphines, including P(t-Bu)3, and PCy3, and other classes of strong donor ligand, such as N-heterocyclic carbenes (entries 6-10). The use of common hydride sources, such as HCO₂H, in conjunction with dt-bpf as ligand was detrimental to the yield of 5a. However, common hydrogen atom donors, such as 1,4cyclohexadiene (1,4-CHD) and γ-terpinene enhanced cyclization efficiency, with the latter providing 5a in 88% yield (entries 12 and 13). These observations provided early evidence for a radical based pathway.15

Cyclization of 1b under optimized 'reductive' aza-Heck conditions, but in the presence of TEMPO (150 mol%) provided trapping adduct 6 in 80% yield and 10:1 d.r.; the structure of the major diastereomer was confirmed by single crystal X-ray diffraction (Scheme 2A). 16 An analogous trapping experiment on 1a, using optimized 'standard' aza-Heck conditions, did not generate 6, and 'standard' aza-Heck product 3a was formed in

Table 1 Ligand effects on the cyclization of oxime esters 1a/b

Entry	R	Pd-source/ligand	Temp/°C	Additive	$3\mathbf{a}^d$ (%)	5 a ^d (%)
1	C_6F_5	Pd ₂ (dba) ₃ /PPh ₃	100	None	30	<5
2	C_6F_5	$Pd_2(dba)_3/P(3,5-(CF_3)_2C_6H_3)_3$	120	None	90	<5
3	C_6F_5	$Pd_2(dba)_3/P(3,5-(CF_3)_2C_6H_3)_3^c$	60	None	93	<5
4	C_6F_5	$(dt-bpf)PdCl_2^b$	120	None	<5	72
5	<i>t</i> -Bu	(dt-bpf)PdCl ₂ ^b	120	None	<5	72
6	t-Bu	Pd ₂ (dba) ₃ /S-Phos	120	None	<5	10
7	t-Bu	$Pd_2(dba)_3/P(1-Ad)_2n-Bu$	120	None	<5	29
8	t-Bu	$Pd_2(dba)_3/P(Cy)_3$	120	None	<5	30
9	t-Bu	$Pd_2(dba)_3/P(t-Bu)_3$	120	None	<5	50
10	t-Bu	PEPPSI-IPr	120	None	<5	27
11	<i>t</i> -Bu	(dt-bpf)PdCl ₂ ^{b,c}	70	None	<5	67
12	t-Bu	$(dt-bpf)PdCl_2^{b,c}$	70	1,4-CHD	<5	80
13	<i>t</i> -Bu	$(dt-bpf)PdCl_2^{b,c}$	70	γ-Terpinene	<5	88

 $[^]a$ 1 : 2 [Pd] : ligand for monodentate systems, 1 : 1 [Pd] : ligand for bidentate systems. b dt-bpf = 1,1'-bis(di-tert-butylphosphino)ferrocene. c 5 mol% Pd/L used. ^d Isolated yield.



Scheme 2 Preliminary mechanistic studies.

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41% yield. The formation of 6 is consistent with cyclization to generate an alkyl radical at C7 during the conversion of 1a/b to 5a, however, in the absence of exogenous hydrogen atom donors, the source of reductant is unclear (cf. Table 1, entry 11 vs. 13). Cyclization of 1b, under the conditions outlined in Table 1, entry 11, using DMF-d₇/Et₃N or DMF-d₇/Et₃N-d₁₅ did not result in appreciable levels of deuterium incorporation in adduct 5a (Scheme 2B). However, in both cases, the yield of 5a was lower than when solely protio-reagents were used. Overall, these observations implicate the feasibility of hydrogen atom abstraction from either DMF, Et₃N, or other components of the reaction system (e.g. 1a/b or 5a).17

TEMPO can trigger radical based pathways when employed as a probe in Pd-catalyzed processes.18 Consequently, the studies outlined in Scheme 2A are not definitive proof for the intermediacy of an alkyl radical during the cyclization of 1a/b to 5a. To provide further evidence, experiments based on Newcomb's radical probe were devised.19 Exposure of O-pivaloyl oxime ester 7a to 'reductive' aza-Heck conditions resulted in the formation of dihydropyrrole 10 in 25% yield and as the only observable product (Scheme 3A); the regioselectivity of cyclopropane cleavage was determined by 2D NMR analysis (see the ESI†). The sole formation of 10 is consistent with initial cyclization to alkyl radical 8, which undergoes selective β-scission (via bond b) to generate stabilized benzylic radical 9. Hydrogen atom abstraction from γ -terpinene then yields 10. Cyclization of O-pentafluorobenzoyl oxime ester 7b, under optimized 'standard' aza-Heck conditions, resulted in a 51% yield and 1:1 ratio of unstable dihydropyrroles 13a/b (Scheme 3B); the latter was formed as a 5.6:1 mixture of alkene isomers. This result is consistent with an imino-palladation pathway, wherein cyclization generates alkyl-Pd(II) intermediate 11. This is not expected to have significant radical (or carbocationic) character, such that *non-selective* β-carbon elimination (to 12a/b) ensues en route to 13a/b.20 Products of β-hydride elimination from alkyl-Pd(II) intermediate 11 were not observed. The studies in

Cyclopropane mechanistic experiments

Scheme 3 provide strong evidence for a radical-based pathway to 5a and an imino-palladation pathway to 3a.

The most likely pathway to alkyl radical 8 is via cyclization of an iminyl radical. The generation of these from oxime esters is documented widely,14 however palladium-catalyzed conditions have not been reported. The oxidative addition of PCy₃ ligated Pd(0)-systems into oxime ester N-O bonds is known, and both Hartwig and Stahl have characterized associated imino-Pd(II) complexes by X-ray diffraction.9,21 However, little is known about the exact nature of the process and further insights were warranted given that, in the present study, PCy₃ leads to radical cyclization product 5a (Table 1, entry 8). To examine this aspect have employed estrone derived oxime esters 14a/

Scheme 4 Estrone mechanistic experiments.

b (Scheme 4); Zard and co-workers have shown that iminyl radicals derived from substrates of this type lead to inversion of the C13 stereocenter.22 Exposure of a DMF solution of O-pivaloyl oxime ester 14a to (dt-bpf)PdCl2 (100 mol%) and Et3N (400 mol%), in the absence of γ-terpinene, resulted in complete consumption of starting material after 15 minutes at 90 °C. After hydrolytic work-up, a 1:5 mixture of estrone derivatives 16a and 16b was isolated in 50% yield. The formation of 16b is consistent with SET from Pd(0) to generate iminyl radical 15a, which undergoes reversible β-scission (via the corresponding nitrile) to afford thermodynamically favored diastereomer 15b. Incomplete inversion of the methyl-substituted stereocenter may be due to quenching of iminyl radical 15a by either hydrogen atom abstraction (from elsewhere in the system) or recombination with Pd(1). An analogous experiment on O-pentafluorobenzoyl oxime ester 14b, using stoichiometric Pd(0)/ $P(3,5-(CF_3)_2C_6H_3)_3$, generated ketone **16a** exclusively in 72% yield. Overall, these results suggest that N-O oxidative addition involving electron rich Pd(0)-systems has significant SET character, whereas electron poor systems insert via a two electron redox pathway. We note that, in certain cases, oxidative addition of Pd(0)-catalysts into alkyl-iodide bonds has been shown to proceed via a SET pathway;4 these observations established that the nature of the substrate can change the mechanistic pathway from that commonly observed for aryl halides (see Scheme 1A). However, the results described in the present study are unique examples where analogous mechanistic deviations are achieved simply by altering the ancillary ligand on Pd. 3,23

Based on the above results, a plausible mechanism for the conversion of 1a/b to 5a is outlined in Scheme 5. Single electron transfer from Pd(0) to oxime ester 1a/b results in N–O cleavage to generate Pd(1) and iminyl radical 17. Studies by the groups of Hartwig and Stahl^{9,21} suggest that, in principle, recombination could generate imino-Pd(11) intermediate 18, however, this work was conducted on systems without an alkene acceptor. Consequently, in the present case, recombination is 'interrupted' by competing and fast 5-*exo* cyclization to generate alkyl radical 19, which is quenched by hydrogen atom abstraction from γ -terpinene to afford product 5a and bis-allylic radical 20. Hydrogen atom transfer from 20 to Pd(1) generates p-cymene and a Pd(11)-hydride, which undergoes base-induced reductive elimination to Pd(0) to close the catalytic cycle. At the present stage, iminyl radical generation via formation and subsequent N–Pd

Scheme 5 A working mechanistic hypothesis.

Table 2 Iminyl radical cyclization scope^a

Starting material	Product	Starting material	Product
PivO _b N	n-Bu—NHH	PivO _N	Ph—H
21a	22a , 47% Yield	Ph 21b, (1:1 d.r.)	22b, 73% Yield
PivO _{nN}	Ph N Me	PivO _b N	(>19:1 d.r.) N Me 4-Pyr
² 21c	22c , 58% Yield	21d	22d, 82% Yield
PivO N N Me Me	Ph H H H H H H H H H H H H H H H H H H H	PivO _N	Ph—N
21e	22e, 71% Yield	21f	22f, 80% Yield

 $[^]a$ Cyclizations were run under the following conditions: (dt-bpf)PdCl₂ (5 mol%), γ-terpinene (400 mol%), Et₃N (400 mol%), DMF (0.1 M), 70–90 °C, 16–24 h. Full details are given in the ESI.

homolysis of imino-Pd(II) intermediate **18** cannot be discounted. The proposed hybrid organometallic radical mechanism is unusual and adds to a growing body of processes that use late transition metal catalysts to accomplish classical radical processes.⁵

The ability to promote iminyl radical cyclizations using a Pd(0)-catalyst, in combination with γ -terpinene, represents a novel and potentially useful approach to alkene hydroamination. Related iminyl-radical based protocols14 often require specialized (and costly) O-activating groups (e.g. O-Ph)14c,f or toxic (e.g. Bu₃SnH/AIBN)14d and/or operationally challenging conditions (e.g. UV/visible light irradiation) that are difficult to scale-up.14ef In light of the efficiency of the conversion of 1b to 5a, we have conducted a preliminary examination of the scope using a range of pivaloyl oxime esters 21a-f (Table 2). Aryl- and alkyl-substituted oximes esters are tolerated and cyclization occurred in moderate to excellent yields using a range of alkene acceptors. For 21b, cyclization of a 1:1 mixture of diastereomers at C2 provided product 22b in high diastereopurity, likely as a result of post-cyclization epimerization to the thermodynamically favored diastereomer.7a The results outlined in Table 2 show that the present protocol provides a useful entry to iminyl radical chemistry.14

Conclusions

In summary, we demonstrate that Pd-catalyzed cyclizations of oxime esters can be partitioned between dichotomous mechanistic manifolds solely through choice of phosphine ligand. Electron rich phosphines promote SET-type oxidative addition, which is 'interrupted' at the stage of an iminyl radical to provide hybrid organometallic radical C–N bond forming cyclizations. For electron poor phosphines, N–O oxidative addition proceeds *via* a 'conventional' two electron pathway to generate directly imino-palladium intermediates, which engage pendant alkenes in a Heck-like manner. These mechanistic insights will guide

ongoing efforts in our laboratory aimed at providing a general aza-Heck protocol. A wide range of processes are dependent upon aza-Pd(II) intermediates generated by N-O oxidative addition, 6-13 and, as such, the studies outlined here are likely to be of importance beyond the immediate area of aza-Heck cyclizations.

Note added after first publication

This article replaces the version published on 1st December 2015, which contained errors in Scheme 2.

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