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Palladium-Catalyzed Synthesis of *N*-Vinyl Pyrroles and Indoles

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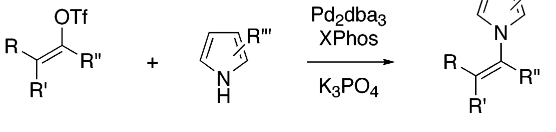
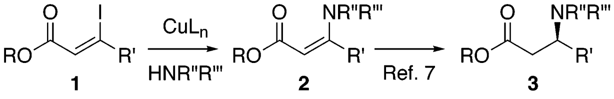


A stereospecific palladium-catalyzed N-vinylation of azaheterocycles with vinyl triflates is described. Cyclic and acyclic vinyl triflates along with nonnucleophilic azaheterocycles were found to be substrates for this palladium-catalyzed synthesis of *N*-vinyl pyrrole and indole derivatives.

Transition-metal-catalyzed carbon−nitrogen bond formation has become a powerful methodology in organic synthesis.[1] A variety of highly active palladium and copper catalyst systems have been reported for the N-arylation of amines, amides, azoles, and carbamates.[2,3] However, there exist fewer examples of C−N bond formation as a method of N-vinylation.[1,4,5] Reports concerning the N-vinylation of dialkylamines and azoles are even more rare as compared to reports of N-vinylation of amides and carbamates.[6,7] A single study on the palladium-catalyzed coupling of lithiated azoles with vinyl bromides has been reported.[6c] Herein we describe a palladium-catalyzed stereospecific coupling of vinyl triflates with pyrroles and indoles.

Recently, Buchwald reported the efficient copper-catalyzed asymmetric conjugate reduction of a variety of 3-aza-2-enoates (**2**) to give the corresponding 3-aza-alkanoates (**3**, eq 1).[7] The necessary 3-aza-2-enoate (**2**) substrates were prepared via a copper-catalyzed N-vinylation of azaheterocycles and lactams with *Z*-3-iodoenoates (**1**).



1 **2** **3** (1)

We were particularly interested in the use of this chemistry for the synthesis of optically active β-azolyl carboxylic acid building blocks for complex alkaloid synthesis. However, the reaction conditions for generating the necessary *Z*-3-iodoenoates (**1**), namely treatment of the corresponding ynoates with sodium iodide in acetic acid at elevated temperatures (60 → 150 °C),[8] were not compatible with several substrates of interest. Furthermore, a similar direct synthesis of the isomeric *E*-3-iodoenoates[9] is not available. We envisioned the use of readily available β-ketoesters as precursors for the stereospecific synthesis of both *Z*- and *E*-β-pyrrolyl enoates **4** (Scheme 1). Specifically, we sought a catalytic method

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(1) (a) Wolfe, J. P.; Wagaw, S.; Marcoux, J.-F.; Buchwald, S. L. *Acc. Chem. Res.* **1998**, *31*, 805−818. (b) Hartwig, J. F. *Acc. Chem. Res.* **1998**, *31*, 852−860. (c) Hartwig, J. F. *Angew. Chem., Int. Ed.* **1998**, *37*, 2046−2067. (d) Yang, B. H.; Buchwald, S. L. *J. Organomet. Chem.* **1999**, *576*, 125−146. (e) Muci, A. R.; Buchwald, S. L. *Top. Curr. Chem.* **2002**, *219*, 131−209. (f) Hartwig, J. F. In *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E., Ed.; Wiley-Interscience: New York, 2002; p 1051.

(2) (a) Wolfe, J. P.; Wagaw, S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 7215−7216. (b) Driver, M. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 7217−7218. For examples of palladium-catalyzed N-arylation of azoles, see: (c) Mann, G.; Hartwig, J. F.; Driver, M. S.; Fernández-Rivas, C. *J. Am. Chem. Soc.* **1998**, *120*, 827−828. (d) Old, D. W.; Harris, M. C.; Buchwald, S. L. *Org. Lett.* **2000**, *2*, 1403−1406. (e) Watanabe, M.; Nishiyama, M.; Yamamoto, T.; Koie, Y. *Tetrahedron Lett.* **2000**, *41*, 481−483.

(3) For examples of copper-catalyzed N-arylation, see: (a) Kiyomori, A.; Marcoux, J.-F.; Buchwald, S. L. *Tetrahedron Lett.* **1999**, *40*, 2657−2660. (b) Collman, J. P.; Zhong, M. *Org. Lett.* **2000**, *2*, 1233−1236. (c) Gujadhur, R. K.; Bates, C. G.; Venkataraman, D. *Org. Lett.* **2001**, *3*, 4315−4317. (d) Klapars, A.; Antilla, J. C.; Huang, X.; Buchwald, S. L. *J. Am. Chem. Soc.* **2001**, *123*, 7727−7729. (e) Klapars, A.; Huang, X.; Buchwald, S. L. *J. Am. Chem. Soc.* **2002**, *124*, 7421−7428. (f) Kwong, F. Y.; Buchwald, S. L. *Org. Lett.* **2003**, *5*, 793−796. (g) Ma, D.; Cai, Q.; Zhang, H. *Org. Lett.* **2003**, *5*, 2453−2455. (h) Padwa, A.; Crawford, K. R.; Rashatasakhon, P.; Rose, M. *J. Org. Chem.* **2003**, *68*, 2609−2617. (i) Antilla, J. C.; Baskin, J. M.; Barder, T. E.; Buchwald, S. L. *J. Org. Chem.* **2004**, *69*, 5578−5587.

(4) For intramolecular palladium-catalyzed N-vinylation of amides, see: (a) Palomo, C.; Aizpurua, J. M.; Legido, M.; Picard, J. P.; Dunogues, J.; Constantieux, T. *Tetrahedron Lett.* **1992**, *33*, 3903−3906. (b) Cuevas, J.-c.; Patil, P.; Snieckus, V. *Tetrahedron Lett.* **1989**, *30*, 5841−5844. (c) Kozawa, Y.; Mori, M. *Tetrahedron Lett.* **2002**, *43*, 111−114. For recent reports on palladium-catalyzed N-vinylation, see: (d) Wallace, D. J.; Klauber, D. J.; Chen, C.-y.; Volante, R. P. *Org. Lett.* **2003**, *5*, 4749−4752. (e) Klapars, A.; Campos, K. R.; Chen, C.-y.; Volante, R. P. *Org. Lett.* **2005**, *7*, 1185−1188.

(5) For a recent review on the use of copper in cross-coupling reactions, see: (a) Beletskaya, I. P.; Cheprakov, A. V. *Coord. Chem. Rev.* **2004**, *248*, 2337−2364. For amidation of vinyl halides with copper as the catalyst or promoter, see: (b) Ogawa, T.; Kiji, T.; Hayami, K.; Suzuki, H. *Chem. Lett.* **1991**, 1443−1446. (c) Shen, R.; Porco, J. A., Jr. *Org. Lett.* **2000**, *2*, 1333−1336. (d) Shen, R.; Lin, C. T.; Porco, J. A., Jr. *J. Am. Chem. Soc.* **2002**, *124*, 5650−5651. (e) Jiang, L.; Job, G. E.; Klapars, A.; Buchwald, S. L. *Org. Lett.* **2003**, *5*, 3667−3669. (f) Han, C.; Shen, R.; Su, S.; Porco, J. A., Jr. *Org. Lett.* **2004**, *6*, 27−30. (g) Pan, X.; Cai, Q.; Ma, D. *Org. Lett.* **2004**, *6*, 1809−1812. (h) Hu, T.; Li, C. *Org. Lett.* **2005**, *7*, 2035−2038. For copper-catalyzed and -promoted N-alkynylation, respectively, see: (i) Frederick, M. O.; Mulder, J. A.; Tracey, M. R.; Hsung, R. P.; Huang, J.; Kurtz, K. C. M.; Shen, L.; Douglas, C. J. *J. Am. Chem. Soc.* **2003**, *125*, 2368−2369. (j) Dunetz, J. R.; Danheiser, R. L. *Org. Lett.* **2003**, *5*, 4011−4014. For a copper-catalyzed C−N bond formation using allenyl halides, see: (k) Trost, B. M.; Stiles, D. T. *Org. Lett.* **2005**, *7*, 2117−2120.

(6) For palladium-catalyzed N-vinylation of amines, see: (a) Barluenga, J.; Fernández, M. A.; Aznar, F.; Valdés, C. *Chem. Commun.* **2002**, 2362−2363. (b) Willis, M. C.; Brace, G. N. *Tetrahedron Lett.* **2002**, *43*, 9085−9088. For palladium-catalyzed N-vinylation of lithiated azoles, see: (c) Lebedev, A. Y.; Izmer, V. V.; Kazyul'kin, D. N.; Beletskaya, I. P.; Voskoboynikov, A. Z. *Org. Lett.* **2002**, *4*, 623−626.

(7) Rainka, M. P.; Aye, Y.; Buchwald, S. L. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 5821−5823.

(8) For the synthesis of *Z*-β-iodoenoates, see: Piers, E.; Wong, T.; Coish, P. D.; Rogers, C. *Can. J. Chem.* **1994**, *72*, 1816−1819.

(9) For synthesis of *E*-β-iodoenoates via an iododestannylation step, see: (a) Thibonnet, J.; Launay, V.; Abarbri, M.; Duchêne, A.; Parrain, J.-L. *Tetrahedron Lett.* **1998**, *39*, 4277−4280. (b) Maguire, R. J.; Munt, S. P.; Thomas, E. J. *J. Chem. Soc., Perkin Trans. 1* **1998**, 2853−2863. (c) Dieter, R. K.; Lu, K. *J. Org. Chem.* **2002**, *67*, 847−855. For isomerization of *Z*-β-iodoenoates, see: (d) Ohba, M.; Kawase, N.; Fujii, T. *J. Am. Chem. Soc.* **1996**, *118*, 8250−8257. (e) Dudley, G. B.; Takaki, K. S.; Cha, D. D.; Danheiser, R. L. *Org. Lett.* **2000**, *2*, 3407−3410.

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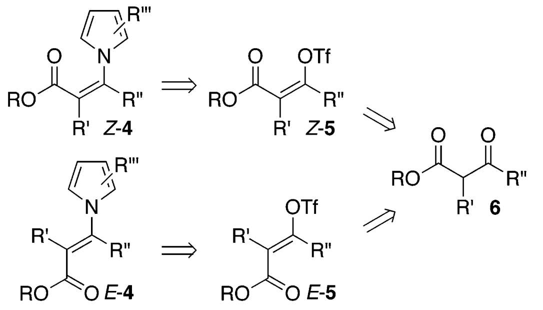
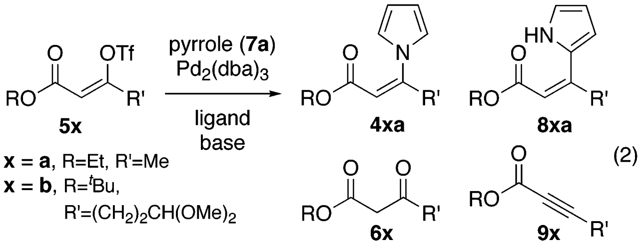
SCHEME 1. Stereospecific Synthesis of β-Pyrrolyl Enoates



for the stereospecific N-vinylation of pyrroles with configurationally defined vinyl triflates.[10]

Initial experiments on the coupling of pyrrole (**7a**) and vinyl triflates **5a**,**b** (eq 2) revealed that copper-based catalyst systems were not effective, typically returning the unreacted triflates. However, the combination of palladium dibenzylideneacetone ($Pd_2(dba)_3$) and 2-dicyclohexylphosphino-2′,4′,6′-triisopropyl-1,1′-biphenyl (XPhos)[11,12] provided a highly active catalyst system for the efficient and selective synthesis of the desired *N*-vinyl pyrroles. Under optimal conditions, the coupling of the vinyl triflate **5a** (1 equiv) with pyrrole (**7a**, 1.5 equiv) using Pd_2dba_3 (5 mol %), XPhos (10 mol %) as ligand in the presence of anhydrous potassium phosphate (1.40 equiv) in toluene at 60 °C proceeded to give the desired *Z*-β-pyrrolyl enoate **4aa** with complete stereospecificity in 84% yield after 3.5 h (Table 1, entry 1). Under identical conditions, the coupling of the more sensitive dimethoxyacetal containing vinyl triflate **5b** afforded the corresponding *N*-vinyl pyrrole **4ba** (eq 2) in 79% isolated yield.[13]



Two commonly observed side products in these coupling reactions were the β-ketoesters **6a**,**b** and the ynoates **9a**,**b** (eq 2). Potassium phosphate tribasic was most effective as the base additive compared to potassium phosphate dibasic, cesium carbonate, triethylamine, and 1,8-diazabicyclo[5.4.0]undec-7-ene; the latter gave predominantly the undesired ynoate byproduct. The use of rigorously dried anhydrous potassium phosphate was found to minimize the formation of both the β-ketoester and the ynoate byproducts.[14,15] Attempted palladium-catalyzed coupling of preformed pyrrolyllithium with vinyl triflate **5b** gave predominantly (~80%) the undesired elimination product **9b** (eq 2).[6c] Furthermore, when *N*-tributylstannylpyrrole[16] was used in place of pyrrole (**7a**) for the synthesis of *N*-vinyl pyrrole **4ba**, in the absence of anhydrous potassium phosphate, the product mixture contained as much as 50% C-coupled product **8ba** (eq 2).[17] Interestingly, this undesired C-coupled byproduct was not observed using pyrrole (**7a**) with the optimal conditions described above.

Considering the synthetic utility of *N*-vinyl pyrroles and indoles and encouraged by these early results, we sought to explore the generality of this catalytic N-vinylation reaction (Table 1). Representative vinyl triflates[18] and azaheterocycles used as substrates in these studies are shown in Chart 1.

The coupling of *Z*-vinyl triflate **5a** with the less nucleophilic acyl pyrrole **7b** at 60 °C affords the desired product **4ab** in 70% yield after 7 h (Table 1, entry 2). An enhancement in the rate of this coupling reaction was noted using dioxane as a cosolvent, affording *N*-vinyl pyrrole derivative **4ab** in 91% isolated yield after 1 h at 60 °C (Table 1, entry 3). Alternatively, increasing the reaction temperature to 80 °C gave **4ab** in 81% yield after complete consumption of starting material (Table 1, entry 4). The coupling of *Z*-vinyl triflate **5a** with the more sterically hindered tetrahydroindolone **7c** was found to be more difficult as compared to the acyl pyrrole **7b** (Table 1, compare entries 2 and 5). The use of toluene−dioxane solvent mixture and higher reaction temperatures slightly increased the yield of this coupling reaction to afford **4ac** in 50% isolated yield (Table 1, entry 7). The coupling of the cyanoindole **7e**, the least reactive azole examined in this study, with *Z*-vinyl triflate **5a** gave only 24% yield of the *N*-vinyl azaheterocycle **4ae** after 48 h (Table 1, entry 8). Both the use of toluene−dioxane solvent mixture and higher reaction temperatures were found to increase the formation of the ynoate **9a** (eq 2) without a net increase in the yield of the coupled product **4ae** (Table 1, entries 9 and 10).[15,19]

To highlight the stereospecificity of this transformation, we examined the coupling between *E*-vinyl triflate **5c** and various azaheterocycles (Table 1, entries 11−17). In every case, the palladium-catalyzed stereospecific C−N bond formation proceeded to afford the desired

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[10] For reviews on the preparation and use of vinyl triflates, see: (a) Ritter, K. *Synthesis* **1993**, 735−762. (b) Baraznenok, I. L.; Nenajdenko, V. G.; Balenkova, E. S. *Tetrahedron* **2000**, *56*, 3077−3119. Also, see: (c) Comins, D. L.; Dehghani, A. *Tetrahedron Lett.* **1992**, *33*, 6299−6302.

[11] Use of XPhos gave superior results as compared to tri-(*o*-tolyl)-phosphine, 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (BINAP), and 2-dicyclohexylphosphino-2′,6′-dimethoxy-1,1′-biphenyl (SPhos).

[12] (a) Tomori, H.; Fox, J. M.; Buchwald, S. L. *J. Org. Chem.* **2000**, *65*, 5334−5341. (b) XPhos is commercially available.

[13] In the absence of palladium catalyst, none of the coupling products were observed.

[14] Best results were obtained by further drying commercially available anhydrous potassium phosphate (160 °C, 0.1 Torr, 12 h) and handling it under inert atmosphere.

[15] For a discussion on the competitive elimination reaction to give ynoates in studies concerning the palladium-catalyzed C−O and C−S bond formation, see: Rossi, R.; Bellina, F.; Mannina, L. *Tetrahedron* **1997**, *53*, 1025−1044.

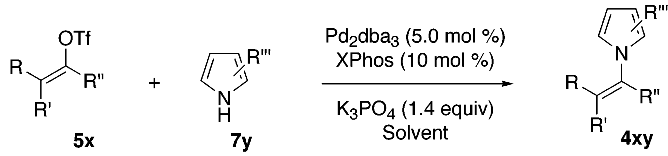
[16] For the synthesis of *N*-(tributylstannyl)pyrrole, see: Williamson, B. L.; Stang, P. J. *Synlett* **1992**, 199−200.

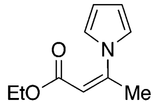
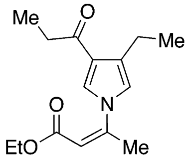
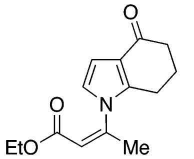
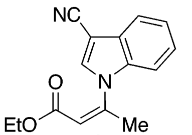
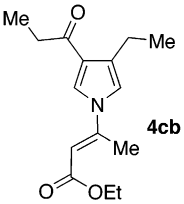
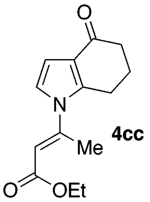
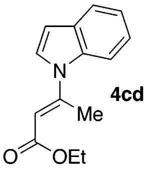
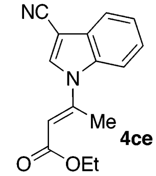
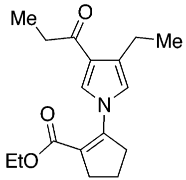
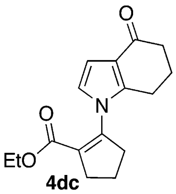
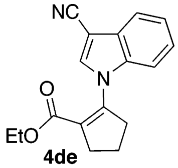
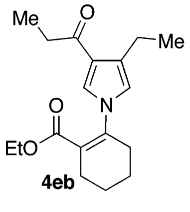
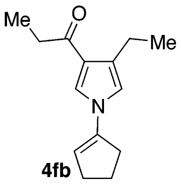
[17] For use of dialkylaminotributystannanes in N-arylation reactions, see: (a) Kosugi, M.; Mameyama, M.; Migita, T. *Chem. Lett.* **1983**, 927−928. (b) Paul, F.; Patt, J.; Hartwig, J. F. *J. Am. Chem. Soc.* **1994**, *116*, 5969−5970. (c) Guram, A. S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 7901−7902.

[18] See Supporting Information for details.

[19] For a discussion on the competitive loss of triflates via nucleophilic attack at the sulfur center during N-arylation of amines with electron-deficient aryl triflates, see: (a) Wolfe, J. P.; Buchwald, S. L. *J. Org. Chem.* **1997**, *62*, 1264−1267. (b) Louie, J.; Driver, M. S.; Hamann, B. C.; Hartwig, J. F. *J. Org. Chem.* **1997**, *62*, 1268−1273.

TABLE 1. Palladium Catalyzed N-Vinylation of Azaheterocycles with Vinyl Triflates

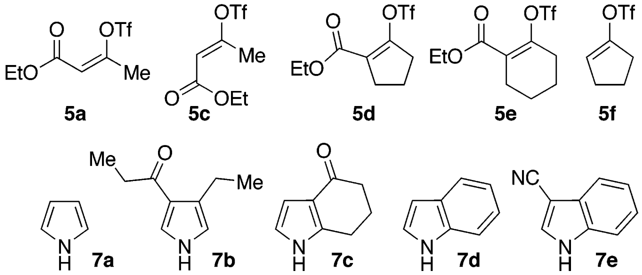


entry	product	temperature (time)^{a}	solvent^{b}	yield^{c}
1	 **4aa**	**60 (3.5)**	**A**	**84**
2	 **4ab**	60 (7)	A	70
3		**60 (1)**	**B**	**91**
4		80 (1.5)	A	81
5	 **4ac**	60 (25)	A	29^{d}
6		60 (1); 80 (6)	B	44
7		**60 (2.5); 80 (7)**	**A**	**50^{d}**
8	 **4ae**	60 (48)	A	24^{d}
9		60 (1); 80 (6)	B	9^{e}
10		60 (2.5); 80 (7)	A	17
11	 **4cb**	60 (2.5); 80 (3)	A	52
12		**60 (0.5); 80 (1.5)**	**B**	**60^{f}**
13	 **4cc**	60 (2.5); 80 (3)	A	29
14		**60 (0.5); 80 (1.5)**	**B**	**73**
15	 **4cd**	**60 (5)**	**A**	**74**
16	 **4ce**	**60 (2.5); 80 (3)**	**A**	**74**
17		60 (0.5); 80 (2.5)	B	71
18	 **4db**	**60 (0.5); 80 (2)**	**B**	**70**
19	 **4dc**	60 (0.5); 80 (3); 95 (3.5)	B	53
20		**60 (0.5); 95 (3.5)**	**B**	**62**
21	 **4de**	60 (0.5); 80 (3); 95 (3.5)	B	18^{g}
22		60 (0.5); 95 (2.5)	B	17^{g}
23	 **4eb**	60 (6); 80 (8)	A	55
24		**60 (2.5); 110 (2.5)**	**A**	**91**
25	 **4fb**	60 (5.5); 80 (18.5)	A	43^{d}
26		**60 (1); 110 (16)**	**A**	**72**

[a] Reaction temperature in degrees Celsius; reaction time in hours. [b] Solvent: A = toluene, B = toluene-1,4-dioxane (3:1). [c] Isolated yield after purification. [d] Remaining vinyl triflate: entry 5, 38%; entry 7, 13%; entry 8, 65%; entry 25, 25%. [e] Complete consumption of **5a**; the ynoate **9a** constitutes the mass balance. [f] Complete conversion to product **4cb** (>90% yield) prior to chromatographic purification. [g] Ethyl 2-oxo-cyclopentanecarboxylate was formed (~50%).

E-enoate. Acyl pyrrole **7b**, tetrahydroindolone (**7c**), indole (**7d**), and 3-cyanoindole (**7e**) were successfully coupled with *E*-vinyl triflate **5c** to give the corresponding *N*-vinyl azaheterocycle in 60, 73, 74, and 74% yield, respectively (Table 1, entries 12, 14, 15, and 16). Interestingly, the *E*-vinyl triflate **5c** demonstrated an enhanced rate of coupling relative to that of the *Z*-vinyl triflate **5a** in all cases examined. Additionally, the coupling reactions employing *E*-vinyl triflate **5c** exhibited a much slower rate of ynoate formation as compared to those using *Z*-vinyl triflate **5a**. Where possible, the use of 1,4-dioxane as a cosolvent and higher reaction temperatures for a

CHART 1



shorter reaction time afforded more efficient palladium-catalyzed N-vinylation.[20] An initial short incubation of the reaction components at 60 °C followed by warming to higher temperatures provided the best results.[21]

The palladium-catalyzed N-vinylation reactions with cyclic vinyl triflates **5d** and **5e** were found to be slower than those of the vinyl triflates **5a** and **5c**. However, the greater thermal stability and the absence of the competing base-induced triflate elimination allowed the use of higher reaction temperatures with these substrates. The coupling of azaheterocycles **7b**, **7c**, and **7e** with triflate **5d** gave the corresponding *N*-vinyl products in 70, 62, and 17% yield, respectively (Table 1, entries 18, 20, and 22). In the latter case a significant quantity (~50%) of ethyl 2-oxo-cyclopentanecarboxylate was isolated, suggesting a competitive sulfonyl transfer reaction.[19] The coupling of the vinyl triflate **5e** with the acyl pyrrole **7b** proceeded efficiently at 110 °C to give the *N*-vinyl pyrrole **4eb** in 91% yield (Table 1, entry 24). Neither of the less reactive azaheterocycles **7c** nor **7e** gave appreciable amounts of the corresponding coupling products with vinyl triflate **5e**.

The coupling of vinyl triflate **5f** with acyl pyrrole **7b** afforded the desired *N*-vinyl azole **4fb** in 72% yield (Table 1, entry 26), demonstrating the possible extension of this chemistry to unactivated vinyl triflates. However, the longer reaction time and the higher reaction temperature needed for the synthesis of product **4fb** should be noted. The reduction of the steric bulk of the vinyl triflate and the presence of the electron-withdrawing ester each have a beneficial effect on the rate of the coupling reaction. The relative rate of coupling for the vinyl triflates discussed here was found to be: **5c** > **5a** > **5d** > **5e** > **5f** (Chart 1). Similarly, the azaheterocycles used in this study may be ranked from most reactive to the least reactive: **7a** > **7b** > **7d** > **7c** > **7e** (Chart 1). While the deprotonation of the heterocycle is facilitated by the presence of an electron-withdrawing substituent, these less nucleophilic heterocycles exhibit a slower overall rate of coupling. Hence, undesired reactions including triflate elimination and sulfonyl transfer reactions may compete when very nonnucleophilic azaheterocycles are used as substrates.[22]

In conclusion, a catalytic method for the stereospecific N-vinylation of azaheterocycles using vinyl triflates was described. Both cyclic and acyclic vinyl triflates were found to be substrates for this palladium-catalyzed synthesis of *N*-vinyl pyrrole and indole derivatives. Successful use of nonnucleophilic azaheterocycles in this coupling reaction is noteworthy. The ready availability of both *E*- and *Z*-vinyl triflates,[23] in conjunction with the herein described chemistry, offers an attractive method for the synthesis of *N*-vinyl azaheterocycles.

Experimental Section

Representative Experimental Procedure. *Z*-3-Pyrrol-1-yl-but-2-enoic Acid Ethyl Ester (4aa, Table 1, Entry 1). Toluene (1.90 mL) was added to an argon-purged sample of Pd$_2$(dba)$_3$ (17.5 mg, 19.1 μmol, 0.05 equiv), XPhos (18.2 mg, 38.1 μmol, 0.10 equiv), and rigorously anhydrous K$_3$PO$_4$ (113 mg, 534 μmol, 1.40 equiv) in a flame-dried flask. Pyrrole (**7a**, 40.0 μL, 572 μmol, 1.50 equiv) was then added, and the deep red mixture was heated to 60 °C. After 30 min, triflate **5a**[24] (100 mg, 381 μmol, 1 equiv) was added via syringe, producing a color change to forest green within approximately 10 min and then to brown within an additional 1 h. After 3.5 h, TLC analysis indicated that the reaction was complete, whereupon the mixture was allowed to cool to 23 °C, was diluted with EtOAc (10 mL), and was vacuum filtered through a plug of Celite (diameter 2.5 cm, height 2.5 cm). The Celite plug and flask were rinsed with an additional 15-mL portion of EtOAc, and the combined organic filtrates were washed with water (7.5 mL) and brine (7.5 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure to give a deep brown residue. Purification of the crude material by flash column chromatography (silica gel: diameter 3.0 cm, height 22 cm; 60% EtOAc/hexanes) afforded the vinyl pyrrole **4aa** (57.1 mg, 84%) as a yellow oil. ^{1}H NMR (500 MHz, CDCl$_3$, 20 °C): 6.90 (app t, J = 2.2 Hz, 2H), 6.23 (app t, J = 2.2 Hz, 2H), 5.52 (q, J = 1.2 Hz, 1H), 4.10 (q, J = 7.1 Hz, 2H), 2.26 (d, J = 1.3 Hz, 3H), 1.20 (t, J = 7.1 Hz, 3H). ^{13}C NMR (125.7 MHz, CDCl$_3$, 20 °C): 165.2, 147.7, 121.4, 110.1, 107.6, 60.5, 24.5, 14.4. FTIR (neat): 2982 (w, C−H), 1718 (s, C═O), 1641 (s, C═C), 1481, 1182, 1051. HRMS-ESI (*m/z*): calcd for C$_{10}$H$_{13}$NO$_2$Na [M + Na]$^+$: 202.0838, found: 202.0839.

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Supporting Information Available: Complete experimental procedures, spectroscopic data, and copies of ^{1}H and ^{13}C NMR spectra for all products. This material is available free of charge via the Internet at http://pubs.acs.org.

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(20) For a discussion on the rate of reductive elimination and C−N bond formation in N-arylation of azaheterocycles, see ref 2c.

(21) The immediate heating of the starting reaction components to temperatures above 60 °C is not recommended. In the case of triflate **5a**, omission of this incubation time resulted in a noticeable decrease in the efficiency of the coupling reaction.

(22) Consistent with this observation, no coupling product was observed using 2-formylpyrrole in conjunction with vinyl triflates **5a**, **5c**, and **5e**. Formation of unreactive (azaheterocyclic)$_n$-palladium complexes due to higher concentration of the aza-anion may also be in part responsible for the observed lower reactivity of acidic azaheterocycles; see ref 2c.

(23) The ease of stereospecific synthesis of fully substituted vinyl triflates as compared to the corresponding vinyl iodides is noteworthy; see refs 8−10.

(24) For the general procedure used to prepare the vinyl triflate **5a**, see: Kim, H.-O.; Ogbu, C. O.; Nelson, S.; Kahn, M. *Synlett* **1998**, 1059−1060.