JOC The Journal of Organic Chemistry

Article

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Preparation of Tetrasubstituted 3-Phosphonopyrroles through Hydroamination: Scope and Limitations

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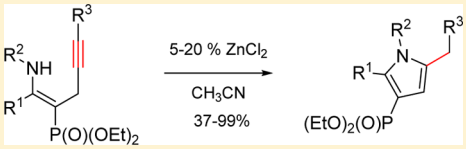
Supporting Information

ABSTRACT: Phosphonylated pyrroles were obtained by a $ZnCl_2$-catalyzed 5-*exo-dig* hydroamination of propargylic enamines. These starting compounds were obtained in two steps from commercially available β-ketophosphonates. The method tolerates a wide variety of substituents at the 1,2- and 5-position of the pyrrole, while further derivatization allows for the introduction of substituents at the 4-position via lithiation or halogenation.



INTRODUCTION

Next to the classical Knorr, Paal–Knorr, and Hantschz pyrrole syntheses and some less prevailing name reactions such as the Barton–Zard or van Leusen transformations, multicomponent reactions as well as cycloadditions have been intensively utilized for the preparation of a range of polysubstituted pyrrole cores. Another frequently applied method is the hydroamination of alkynes in order to furnish polysubstituted pyrroles using, among others,[1] gold,[2−4] silver,[5−7] titanium,[8,9] and platinum catalysts.[10−15] Only in some cases were 3-pyrrolyl phosphonates obtained.[16−20] Beller and co-workers recently published a versatile Ru-catalyzed three-component reaction involving ketones, amines and vicinal diols, which is applicable to phosphonates.[21] Larionov and de Meijere reported on the formal cycloaddition of α-metalated isocyanides to acetylenes leading to pyrroles,[22,23] and Demir and Tural transformed α-cyanomethyl-β-ketoesters into pyrrole-3-phosphonates.[24]

Phosphonylated pyrroles are of interest because of their presence in bioactive molecules. Analgesic properties have been ascribed to 2-phosphonopyrroles,[25] and 2-phosphonoindoles display thyromimetic,[26] anti-inflammatory,[27] and plant growth regulating properties.[28] Furthermore, 3-carboxylpyrroles, of which the phosphonates are bioisosteres, have been reported as cyclic AMP-specific phosphodiesterase inhibitors.[29] Retrosynthetically, we envisioned a Lewis acid catalyzed cycloisomerization-type pyrrole assembly, starting from phosphonylated propargylic imines, which themselves could be obtained from β-ketophosphonates (Scheme 1).

RESULTS AND DISCUSSION

The imination of β-ketophosphonates **1a,e–g** under Dean–Stark conditions proceeded in excellent yields.[30,31] Several amines were used in combination with various substrates to explore the scope of the subsequent reactions (Table 1). Electron-donating (entry f) as well as electron-withdrawing aromatic moieties (entry e) were tolerated as R^1, while aliphatic groups could also be used (entry g). While conversion was clean and quantitative, the obtained crude product consists of enamines **2a–g** while the imines **3a–g** are present in both their (*E*) and (*Z*) forms, with the majority in the (*E*)-configuration due to steric hindrance between the R^2 substituent and the bulky phosphonate group.

The introduction of an alkyne moiety was achieved by treating the enamine/imine mixture with LiHMDS at −78 °C, leading to the formation of the corresponding aza-enolate, followed by the addition of propargyl bromide **4** and allowing the reaction mixture to warm to room temperature (Table 2). Other strong bases such as *n*-BuLi, LDA, or NaH could be employed as well. The reaction progress was monitored using ^{31}P NMR spectroscopy, which indicated it was difficult to obtain complete conversion. Therefore, additional base and electrophile were consecutively added until complete conversion was achieved. However, formation of bis-propargylated products was inevitable, and these compounds have retention factors that are similar to those of the desired products **5a–j**, accounting for diminished yields after purification via column chromatography.

In order to simplify the reaction sequence, we evaluated first propargylating the β-ketophosphonates **1** before performing the iminations. Unfortunately, the subsequent imination reaction failed, resulting in full recovery of starting material **1**. This was probably due to increased steric hindrance upon introduction of the propargyl moiety, blocking amine attack across the carbonyl bond. Having produced terminal alkynes **5a–g**, nonterminal alkynes could also be synthesized and evaluated toward hydroamination. This could be done by performing a Sonogashira coupling using terminal alkynes **5a–g** as substrates, but this would require an extra step in the sequence. The alternative was to use nonterminal propargyl bromides **4** and add these to the aza-enolates obtained from **2** and **3**. However, in this manner one is limited to the commercially available propargylic bromides. A few nonterminal alkynes were produced this way (R^3 = CH_3, 1-naphthyl, $SiMe_3$). For R^1 = Me though (Table 2, entry g), introduction of the propargyl moiety proved a lot more

Received: January 20, 2014
Published: April 18, 2014

Scheme 1. Retrosynthetic Approach to 3-Phosphonopyrroles

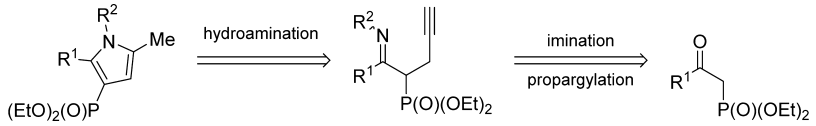
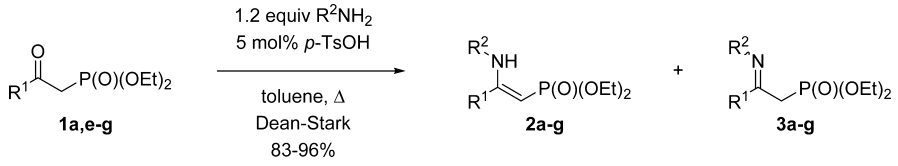


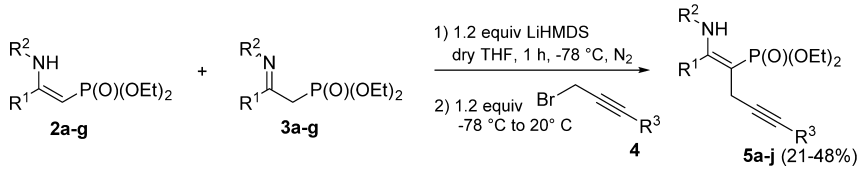
Table 1. Preparation of Diverse Phosphonylated Enamines 2a−g and Imines 3a−g: Reaction Yields and Ratios of Conformations Based on ^{1}H and ^{31}P NMR



entry	R^1	R^2	**2** + **3** (%)	**2**/**3**	**3***E*/*Z*
a	Ph	benzyl	95	60/40	63/37
b	Ph	allyl	98	83/17	83/17
c	Ph	*n*-butyl	87	77/23	76/24
d	Ph	phenyl	96	69/31	85/15
e	4-F-C_6H_4	benzyl	92	57/43	85/15
f	4-OCH_3-C_6H_4	benzyl	83	70/30	55/45
g	CH_3	benzyl	94	63[a]/37	63/37

[a]The enamine is present in both the (*E*)- and (*Z*)-form in a ratio of 2/1, respectively.

Table 2. Introduction of the Propargylic Moiety onto Products 2 and 3



entry	R^1	R^2	R^3	**5** (%)
a	Ph	benzyl	H	41
b	Ph	allyl	H	21
c	Ph	*n*-butyl	H	48
d	Ph	phenyl	H	31
e	4-F-C_6H_4	benzyl	H	37
f	4-OCH_3-C_6H_4	benzyl	H	43
g	CH_3	benzyl	H	94[a]
h	Ph	benzyl	CH_3	46
i	Ph	benzyl	1-naphthyl	38
j	Ph	benzyl	$SiMe_3$	45

[a]Crude yield, as **5g** is unstable and degrades during column chromatography.

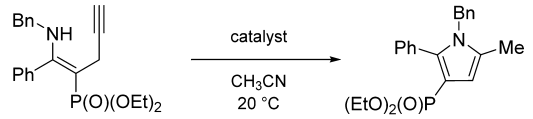
challenging than for the other substrates, probably due to the acidic methyl group. Attempted purification through column chromatography led to severe degradation, so the next step was performed using the crude product.

The obtained α-propargyl phosphonates **5a−j** were mostly present in the (*Z*)-enamine form based on the coupling constants $^{3}J_{CP}$ of ca. 18 Hz,[32] although some (*E*)-isomer was also present. For both terminal alkynes **5a−g** and internal alkynes **5i−j** the *E*/*Z* ratio is around 1/9 while for the internal alkyne **5h** the ratio is 1/4.

With propargylated enamines **5a−j** in hand, we next envisioned a regioselective 5-*exo*-*dig* hydroamination reaction leading to phosphonylated pyrroles. A literature search resulted in a copious amounts of references regarding hydroamination catalysts, solvents, and the substrate scope for the synthesis of pyrroles.[33−45] Based on our own work regarding transition-metal-catalyzed cyclization reactions,[46−48] several Au catalysts were evaluated at first with **5a**, albeit with mediocre results (Table 3, entries a−c). Hydrolysis of the enamine took place along with some formation of the desired pyrrole **6a**. Application of gold chlorides under nonanhydrous conditions leads to in situ hydrochloric acid formation which could account for the observed hydrolysis. Indeed, 0.2 equiv of aqueous hydrochloric acid only led to hydrolysis of the starting material and precipitation, probably due to salt formation (entry d). Other acids such as TFA also induced hydrolysis instead of hydroamination (entry e). Application of $ZnCl_2$ yielded the desired pyrrole in quantitative yield after 1 day, while $AgNO_3$ did the job in merely 1 h (entries f and i). Both Pd- and Cu-acetates were less suitable (entries l, m). Next, the catalyst loading was diminished to 5 and 1 mol % for both $ZnCl_2$ and $AgNO_3$, and the reaction times were compared (entries g, h, j, k). For $ZnCl_2$ there was no difference between a catalyst loading of 20 and 5 mol %. Further

dx.doi.org/10.1021/jo500139z | J. Org. Chem. 2014, 79, 4322−4331

Table 3. Catalyst Screening for Pyrrole Synthesis through Hydroamination



5a **6a**

entry	catalyst	amt (mol %)	reaction time (h)	**6a** (%)
a	AuCl	20	4	50[a]
b	$AuCl_3$	20	5	41[a]
c	$HAuCl_4$	20	4	73[a]
d	HCl	20	24	0
e	TFA	20	24	0
f	$ZnCl_2$	20	24	99
g	$ZnCl_2$	5	24	99
h	$ZnCl_2$	1	144	99
i	$AgNO_3$	20	1	99
j	$AgNO_3$	5	2	94[a]
k	$AgNO_3$	1	48	62[a]
l	$Pd(OAc)_2$	20	4	23[a]
m	$Cu(OAc)_2$	20	24	32[a]

[a]After column chromatography.

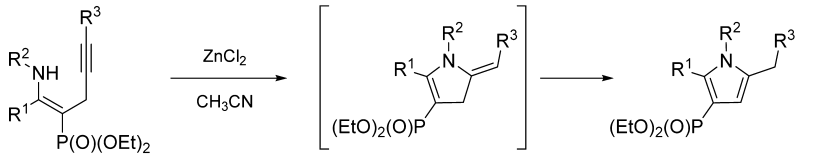
lowering to 1 mol % resulted in a severe rate decrease, prolonging the reaction to 144 h (entries f–h). Upon application of 5 mol % $AgNO_3$ the reaction time doubled, while use of 1 mol % required 48 h for the reaction to complete. However, longer exposure to $AgNO_3$ led to some slight degradation, resulting in lower yields (entries j, k). Furthermore, we noticed that refluxing the enamine **5a** in toluene with a catalytic amount of *p*-TsOH also yielded the desired pyrrole **6a**, but given pyrrole's tendency to polymerize the room temperature catalytic approach was preferred. Due to these observations and as $AgNO_3$ is a factor of 25 more expensive than $ZnCl_2$ (ca. 2000 €/kg vs 80 €/kg), the latter was chosen at a loading of 5 mol % for the further elaboration of the reaction scope in spite of the discrepancy in reaction rate. In the literature, Zn salts have often been applied for the hydroamination of alkynes.[49−61]

Having identified a suitable catalyst, further optimization of the reaction conditions indicated that the transformation also proceeded cleanly in CH_2Cl_2, THF, and toluene but at a slower rate. Therefore, CH_3CN remained the solvent of choice. Application of these optimized hydroamination conditions to the propargylic enamines **5** led to the desired pyrroles in good to excellent yields (Table 4). The choice of R^1 and/or R^2 does not seem to significantly influence the reaction. However, the nonterminal alkynes **5h–j** did not furnish the pyrroles **6h–j** under these conditions, and only starting material was recovered after 24 h. The reaction was therefore continued at reflux temperature (82 °C), and this did deliver the aspired pyrroles **6h–j** along with hydrolysis of the starting enamines **5h–j**. Consequently, these substrates were transformed using 20 mol % of dried $ZnCl_2$ in dry CH_3CN in order to speed up pyrrole formation and counteract hydrolysis. For R^3 = $SiMe_3$ though (entry j), no pyrrole was detected even after 7 days reaction at reflux temperature. This may be attributed to electronic effects, as Si is more electropositive than sp^3- and sp^2-hybridized C and accordingly deactivates the alkyne bond for hydroamination.

Thus, a general method for the preparation of 1,2,5-substituted 3-phosphonopyrroles was developed. Retrosynthetically, the introduction of substituents at the 4-position would require the use of branched propargyl halides **4** or the obtained pyrroles **6** had to be derivatized. The first option proved to be troublesome, since branched propargyl halides are not commercially available and the introduction of the propargyl group is the most difficult step in our synthesis. Therefore, we opted for the development of a general method for derivatization at the 4-position of the obtained pyrroles **6**.

The most straightforward possibility was deprotonating the pyrrole C–H using a strong base followed by subsequent quenching with a suitable electrophile (Table 5, method A). While a benzylic proton is present in **6c** which can potentially be deprotonated, literature examples prove the feasability of this approach.[62] Initial attempts to deprotonate the pyrrole using *n*-

Table 4. Isolated Yields and Reaction Times for the Hydroamination of Enamines 5a–j with Formation of the Corresponding Pyrroles 6a–i[a]



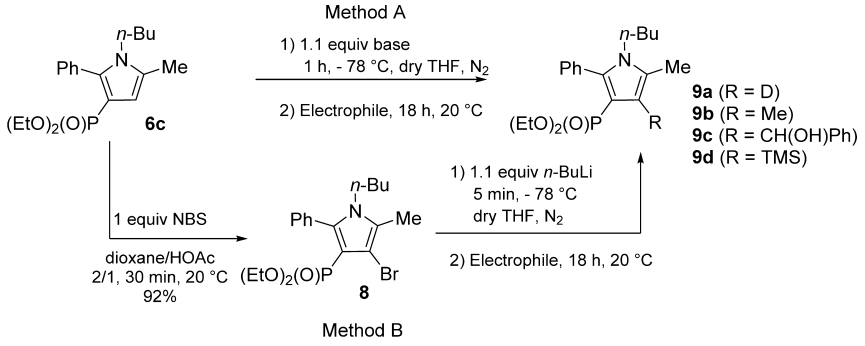
5a-j **7a-j** **6a-j** (10-99%)

entry	R^1	R^2	R^3	time	**6** (%)
a	Ph	benzyl	H	24 h	99
b	Ph	allyl	H	20 h	89
c	Ph	*n*-butyl	H	20 h	94
d	Ph	phenyl	H	20 h	91
e	4-F-C_6H_4	benzyl	H	24 h	97
f	4-OCH_3-C_6H_4	benzyl	H	24 h	72[b]
g	CH_3	benzyl	H	45 min	10[b,c]
h	Ph	benzyl	CH_3	7 d	46[b]
i	Ph	benzyl	1-naphthyl	24 h	37[b]
j	Ph	benzyl	$SiMe_3$	3 d	

[a]Conditions for terminal alkynes **5a–g**: 5 mol % of $ZnCl_2$, CH_3CN, rt, air. Nonterminal alkynes **5h–j**: 20 mol % of dried $ZnCl_2$, dry CH_3CN, Δ, N_2. [b]After column chromatography. [c]Yield over two steps. Crude starting material **5g** was used and catalyst was added based on this weight, so more than 5 mol % of catalyst was added which accounts for the shorter reaction time.

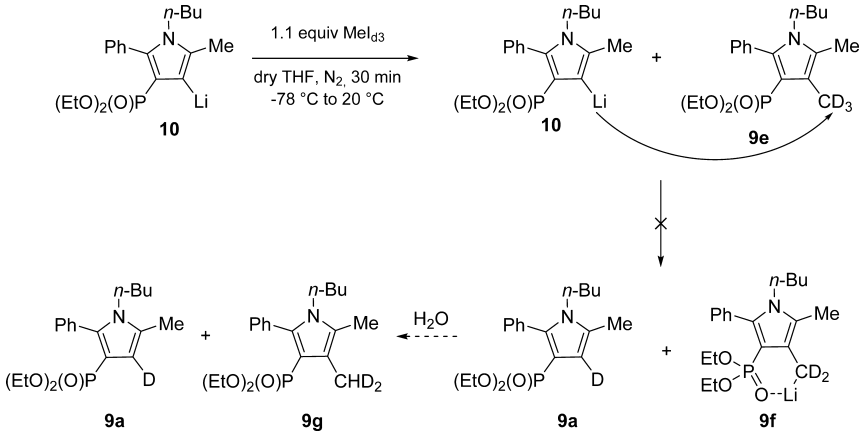
dx.doi.org/10.1021/jo500139z | J. Org. Chem. 2014, 79, 4322–4331

Table 5. Derivatization at the 4-Position of Pyrrole 6c



entry	method	base	electrophile (equiv)	additive (equiv)	product ratio **6c** (%)	product ratio **9** (%)
a	A	*n*-BuLi	D_2O (excess)		40	60
b	A	*n*-BuLi	MeI (1.1)		79	21
c	A	*n*-BuLi	benzaldehyde (1.1)		100	0
d	A	*s*-BuLi	D_2O (excess)		0	100
e	A	*s*-BuLi	MeI (1.1)		38	62
f	A	*t*-BuLi	MeI (1.1)		100	0
g	B	*n*-BuLi	MeI (1.1)		40	60
h	B	*n*-BuLi	MeI (10)		31	69
i	B	*n*-BuLi	MeI (10)	AgF (1.2)	36	64
j	B	*n*-BuLi	MeI (10)	12-crown-4 (1.2)	40	60
k	B	*n*-BuLi	MeI-d_3 (1.1)		26	74
l	B	*n*-BuLi	TMSCl (1.1)		98	trace
m	B	*n*-BuLi	benzaldehyde (1.1)		100	0

Scheme 2. Quench with Iodomethane-d_3 To Verify the Hypothesis of Intermolecular Deprotonation after Li−Br Exchange and Addition of Iodomethane

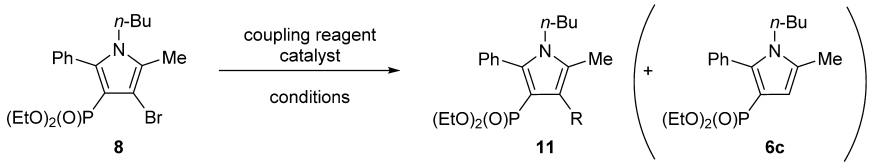


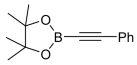
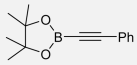
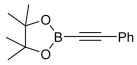
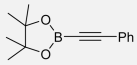
BuLi were only partly successful as no complete conversion could be attained after the addition of several electrophiles. Reaction with D_2O resulted in 60% deuteration, and with the somewhat bulkier iodomethane only 21% **9b** was obtained (entries a, b). Using benzaldehyde as an electrophile did not lead to any alkylation (entry c). Benzaldehyde is most likely too large to approach the lithiated anion which is in the plane of the pyrrole ring and is shielded by the phosphonate group. Application of stronger bases such as *s*-BuLi led to full deuteration, proving complete deprotonation of product **6c** (entry d). Use of iodomethane for alkylation only led to 62% of product, as a result of steric hindrance (entry e). Interestingly, *t*-BuLi did not deprotonate the pyrrole **6c** which is again attributed to steric hindrance (entry f). It is noteworthy that under these conditions no deprotonation of the methyl group on the 5-position of **6c** occurs at all, not even when using *t*-BuLi.

Another effort to functionalize the pyrroles involved bromination and subsequent lithium−bromine exchange (Table 5, method B).[63] The introduction of the bromine atom proceeded smoothly, but attempted methylation proved just as difficult as after direct deprotonation, although method B gave cleaner results (entry g). Even a large excess of iodomethane (entry h) did not improve conversion, nor did the addition of AgF to precipitate AgI or the addition of 12-crown-4 to scavenge the lithium ions (entries i, j). Iodomethane-d_3 was used in entry k to investigate whether the newly introduced methyl group at the 4-position of **9e** was acidic enough to quench the remainder of the starting material **10**, but this was not the case (Scheme 2). Introducing larger electrophiles also failed (entries l and m).

dx.doi.org/10.1021/jo500139z | J. Org. Chem. 2014, 79, 4322−4331

Table 6. Transition Metal-Catalyzed Coupling of Pyrrole 8 to sp, sp^2, and sp^3 Carbon Atoms



entry	coupling reagent (equiv)	catalyst	conditions	product ratio[a] (%) 8	6c	11
a	TMS (1.2)	2 mol% $PdCl_2(PPh_3)_2$ 1 mol% CuI	Et_3N, N_2 60 h, Δ	100	0	0
b	TMS (1.2)	2 mol% $PdCl_2(PPh_3)_2$ 1 mol% CuI	μW, Et_3N 1 h, 130 °C	100	0	0
c	TMS (1.2)	2 mol% $Pd(PPh_3)_4$ 1 mol% CuI	μW, Et_3N 1 h, 130 °C	100	0	0
d	TMS (1.2)	2 mol% $PdCl_2(PPh_3)_2$ 1 mol% CuI	1 equiv Et_3N μW, DME/H_2O 3/1 1 h, 130 °C	100	0	0
e	 (1.3)	5 mol% $Pd(PPh_3)_4$	2 equiv Na_2CO_3 μW, DME/H_2O 3/1 1 h, 130 °C	15	85	0
f	 (1.3)	5 mol% $Pd(PPh_3)_4$	2 equiv Na_2CO_3 μW, DME/H_2O 3/1 2 h, 130 °C	0	60	40
g	 (3.0)	5 mol% $Pd(PPh_3)_4$	3 equiv Na_2CO_3 μW, DME/H_2O 3/1 2 h, 130 °C	degradation		
h	 (1.3)	5 mol% $Pd(PPh_3)_4$	2 equiv Na_2CO_3 μW, DME/H_2O 3/1 4 h, 130 °C	degradation		
i	Bu_3Sn—≡—Ph (3.0)	5 mol% $Pd(PPh_3)_4$	μW, DMF 2 h, 130 °C	40	0	60
j	Bu_3Sn—≡—Ph (3.0)	5 mol% $Pd(PPh_3)_4$	μW, DMF 4 h, 130 °C	25	0	75
k	Bu_3Sn (1.2)	5 mol% $Pd(PPh_3)_4$	DMF, N_2 60 h, 100 °C	100	0	0
l	Bu_3Sn (3.0)	5 mol% $Pd(PPh_3)_4$	μW, DMF 2 h, 130 °C	52	0	48
m	$(HO)_2B$—Ph (1.3)	5 mol% $Pd(PPh_3)_4$	2 equiv Na_2CO_3 μW, DME/H_2O 3/1 1 h, 130 °C	0	21	79 (63)[b]
n	Bu_3Sn (3.0)	5 mol% $Pd(PPh_3)_4$	DMF, N_2 60 h, 100 °C	100	0	0
o	Bu_3Sn (3.0)	5 mol% $Pd(PPh_3)_4$	μW, DMF 3 h, 130 °C	20	10	70 (43)[b]

[a]Based on ^{31}P NMR. [b]Isolated yield.

An alternative to lithiation followed by alkylation is transition metal-catalyzed cross-coupling. The 4-bromopyrrole **8** was subjected to standard cross-coupling procedures in order to join the pyrrole core to an sp-, sp^2-, and sp^3-hybridized carbon

dx.doi.org/10.1021/jo500139z | J. Org. Chem. 2014, 79, 4322−4331

atom.[64] The results are depicted in Table 6. Attempted Sonogashira coupling yielded unreacted starting material under both classical and microwave heating (entries a–d). As an alternative, Suzuki coupling with 2-phenyl-1-ethynylboronic acid pinacol ester was evaluated. After 1 h at 130 °C under microwave irradiation (entry e), mainly debrominated product **6c** was recovered, indicating that oxidative addition had taken place but the transmetalation or reductive elimination steps did not proceed. Prolonging the reaction time to 2 h (entry f) resulted in the formation of some coupled product and complete consumption of the starting material, along with product degradation. However, increasing the amount of boronic ester (entry g) or further prolonging the reaction time (entry h) did not lead to better results. Next, Stille coupling with tributyl(phenylethynyl)tin was assessed. After 2 h of microwave irradiation (entry i), 60% of coupled product was observed and after 4 h reaction the conversion to **11** was increased to 75% (entry j). Longer reaction times did not lead to full conversion of **8**, which was chromatographically inseparable from the coupled product.

Coupling of the pyrrole core to sp^2 carbon atoms was performed by Stille coupling (entries k, l) and Suzuki coupling (entry m). The Stille coupling was successful only under microwave irradiation (48% of **11l**), but the coupled product could not be isolated in analytically pure form. The Suzuki coupling proceeded cleanly, resulting in the isolation of 63% of **11m**. Increasing the reaction time did not lead to improved conversion to **11m**. An sp^3 carbon was coupled to the pyrrole core in 43% isolated yield using allyltributyltin under microwave irradiation (entry o), whereas conventional heating yielded exclusively starting material (entry n). Overall, the best results were obtained using Stille cross-coupling methodology.

CONCLUSION

In summary, β-ketophosphonates were subjected to imination and α-propargylation reactions, the latter being the most difficult step. Subsequently, the obtained phosphonylated enamines were transformed into the corresponding pyrroles through a $ZnCl_2$-catalyzed 5-*exo*-*dig* hydroamination which proceeded smoothly for terminal alkynes. Nonterminal alkynes needed higher catalyst loading and increased temperatures to effectively undergo cyclization. Derivatization at the 4-position of the pyrrole via direct lithiation was feasible but inefficient for larger electrophiles. Electrophilic bromination with NBS proved efficient, but subsequent lithium–bromine exchange did not facilitate further derivatization. Instead, various cross-coupling strategies were evaluated. High temperatures and microwave irradiation were required in order to successfully couple the pyrrole core to sp, sp^2, and sp^3 carbon atoms.

EXPERIMENTAL SECTION

Commercially available products were used as received without any purification unless otherwise noted. Column chromatography was performed in a glass column with silica gel (particle size 70–200 μm, pore diameter 60 Å) using mixtures of ethyl acetate (EtOAc) and hexanes. Preparative TLC was executed with 2000 μm 20 × 20 cm TLC plates. NMR spectra were recorded at 300 and 400 MHz (^{1}H), 121 and 167 MHz (^{31}P), 75 and 100 MHz (^{13}C), and 376 MHz (^{19}F) in $CDCl_3$ unless otherwise noted. Low-resolution mass spectra were obtained with a single quadrupole mass spectrometer (ESI, 70 eV). High-resolution mass spectra were obtained with a time-of-flight (TOF) mass spectrometer (ESI or APCI).

Synthesis of Enamino- and Iminophosphonates 2/3a–g. Diethyl (2-oxo-2-phenylethyl)phosphonates **1** were dissolved in toluene (1 mL/mmol) in a round-bottom flask equipped with a Dean–Stark apparatus. An appropriate primary amine (1.2 equiv) and *p*-TsOH monohydrate (0.05 equiv) were added, and the reaction mixture was heated to reflux temperature and left overnight. The reaction progress was monitored using gas chromatography. After all starting material had been consumed, the solvent was removed in vacuo and the residue was redissolved in diethyl ether and washed with aqueous $NaHCO_3$. The organic phase was extracted with diethyl ether (3 × 20 mL), dried over $MgSO_4$, and concentrated in vacuo.

Synthesis of Propargylic Enaminophosphonates 5a–j. In a flame-dried round-bottom flask, enaminophosphonates **2a–g** were dissolved in dry THF (0.5 mmol/mL) and put under an inert N_2-atmosphere. The solution was cooled to −78 °C before adding LiHMDS (1.2 equiv) and was kept stirring at −78 °C for 1 h. Next, a propargyl bromide solution in toluene (1.2 equiv) was added in a dropwise fashion and the reaction mixture was allowed to warm to 20 °C. Reaction progress was monitored using HPLC. If no further conversion took place, additional LiHMDS and propargyl bromide were added until no more starting material was present. Water was added and the solution was extracted using diethyl ether (3x 20 mL). After drying the combined organic layers over $MgSO_4$, the solvent was removed in vacuo and the residue was purified using column chromatography. *E*/*Z* mixtures were obtained but only the peaks of the major isomers were assigned.

*Diethyl (Z)-(1-(Benzylamino)-1-phenylpent-1-en-4-yn-2-yl)phosphonate (**5a**).* 317 mg (0.92 mmol) of **2a**/**3a** was converted into **5a**. After column chromatography, 144 mg of **5a** was obtained (0.38 mmol, 41% yield, brown oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 1.36 (6H, t, J = 7.1 Hz), 1.84 (1H, t, J = 2.2 Hz), 2.62 (2H, dd, $^3J_{HP}$ = 16.5 Hz, J = 2.2 Hz), 3.91 (2H, d, J = 6.5 Hz), 4.11 (4H, dq, $^3J_{HP}$ = 8.3 Hz, J = 7.2 Hz), 7.08–7.10 (2H, m), 7.19–7.26 (4H, m), 7.36–7.43 (4H, m), 8.30 (1H, t, J = 6.5 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 16.4 (d, $^3J_{CP}$ = 6.9 Hz), 18.6 (d, $^2J_{CP}$ = 10.4 Hz), 48.6, 61.3 (d, $^2J_{CP}$ = 4.6 Hz), 67.0, 81.8 (d, $^1J_{CP}$ = 184.6 Hz), 84.8, 126.9, 127.1, 128.4, 128.5, 128.9, 134.8 (d, $^3J_{CP}$ = 17.3 Hz), 140.1, 165.0 (d, $^2J_{CP}$ = 13.9 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 24.35 (m), 27.31 (M). IR (cm^{-1}) ν_{max}: 1021 (P–O), 1050 (P–O), 1205 (P═O), 1589, 1606, 2113, 2980, 3288. MS (ESI, pos) *m*/*z*: 384.2/385.2 (M + H$^+$, 100/25). HRMS: *m*/*z* calcd for $C_{22}H_{27}NO_3P$ (M + H)$^+$ 384.1723, found 384.1734. Chromatography: hexanes/EtOAc 7/3, R_f = 0.26.

*Diethyl (Z)-(1-(Allylamino)-1-phenylpent-1-en-4-yn-2-yl)phosphonate (**5b**).* 300 mg (1.02 mmol) of **2b**/**3b** was converted into **5b**. After column chromatography, 71 mg of **5b** was obtained (0.21 mmol, 21% yield, brown oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 1.37 (6H, t, J = 7.2 Hz), 1.86 (1H, t, J = 2.3 Hz), 2.61 (2H, dd, $^3J_{HP}$ = 16.5 Hz, J = 2.3 Hz), 3.32 (2H, dd, J = 6.1 Hz, J = 5.0 Hz), 4.14 (4H, dq, $^3J_{HP}$ = 7.2 Hz, J = 7.2 Hz), 5.03 (1H, dd, J_Z = 9.9 Hz, J = 1.1 Hz), 5.13 (1H, dd, J_E = 17.1 Hz, J = 1.4 Hz), 5.68 (1H, ddt, J_E = 17.1 Hz, J_Z = 9.9 Hz, J = 5.0 Hz), 7.29–7.33 (2H, m), 7.40–7.41 (3H, m), 7.96 (1H, t, J = 6.1 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 16.3 (d, $^3J_{CP}$ = 6.9 Hz), 18.5 (d, $^2J_{CP}$ = 10.4 Hz), 46.9, 61.3 (d, $^2J_{CP}$ = 4.6 Hz), 66.9, 80.6 (d, $^1J_{CP}$ = 188.0 Hz), 84.9, 115.3, 128.3, 128.5, 128.8, 134.8 (d, $^3J_{CP}$ = 17.3 Hz), 136.1, 165.0 (d, $^2J_{CP}$ = 12.7 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 24.41 (m), 27.47 (M). IR (cm^{-1}) ν_{max}: 1021 (P–O), 1050 (P–O), 1204 (P═O), 1587, 1607, 2114, 2981, 3288. MS (ESI, pos) *m*/*z*: 334.3/335.3 (M + H$^+$, 100/25). HRMS: *m*/*z* calcd for $C_{18}H_{25}NO_3P$ (M + H)$^+$ 334.1567, found 334.1574. Chromatography: hexanes/EtOAc 7/3, R_f = 0.20.

*Diethyl (Z)-(1-(Butylamino)-1-phenylpent-1-en-4-yn-2-yl)phosphonate (**5c**).* 418 mg (1.34 mmol) of **2c**/**3c** was converted into **5c**. After column chromatography, 224 mg of **5c** was obtained (0.64 mmol, 48% yield, brown oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 0.71 (3H, t, J = 7.2 Hz), 1.12–1.22 (2H, m), 1.25–1.30 (8H, m), 1.78 (1H, t, J = 2.8 Hz), 2.51 (2H, dd, $^3J_{HP}$ = 16.5 Hz, J = 2.8 Hz), 2.60 (2H, td, J = 6.6 Hz, J = 6.1 Hz), 4.04 (4H, dq, $^3J_{HP}$ = 8.6 Hz, J = 7.2 Hz), 7.21–7.25 (2H, m), 7.29–7.36 (3H, m), 7.38 (1H, t, J = 6.1 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 13.7, 16.3 (d, $^3J_{CP}$ = 6.9 Hz), 18.3 (d, $^2J_{CP}$ = 10.4 Hz), 19.8, 33.0, 44.4, 61.1 (d, $^2J_{CP}$ = 4.6 Hz), 66.8, 79.2 (d, $^1J_{CP}$ = 188.1 Hz), 85.0, 128.2, 128.4, 128.6, 135.2 (d, $^3J_{CP}$ = 17.3 Hz), 165.3 (d, $^2J_{CP}$ = 12.7 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 24.51 (m), 27.88 (M). IR (cm^{-1}) ν_{max}: 1022 (P–O), 1052 (P–O), 1203 (P═O), 1588, 1607, 2176, 2932,

dx.doi.org/10.1021/jo500139z | J. Org. Chem. 2014, 79, 4322–4331

3283. MS (ESI, pos) m/z: 350.3/351.3 (M + H^+, 100/25). HRMS: m/z calcd for $C_{19}H_{29}NO_3P$ (M + H)$^+$ 350.1880, found 350.1878. Chromatography: hexanes/EtOAc 8/2, R_f = 0.16.

*Diethyl (Z)-(1-Phenyl-1-(phenylamino)pent-1-en-4-yn-2-yl)phosphonate (**5d**).* 495 mg (1.50 mmol) of **2d**/**3d** was converted into **5d**. After column chromatography, 172 mg of **5d** was obtained (0.47 mmol, 31% yield, yellow oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 1.37 (6H, td, J = 7.2 Hz, $^4J_{HP}$ = 1.1 Hz), 2.01 (1H, t, J = 2.8 Hz), 2.85 (2H, dd, $^3J_{HP}$ = 16.5 Hz, J = 2.8 Hz), 4.18 (4H, dq, $^3J_{HP}$ = 8.3 Hz, J = 7.2 Hz), 6.51 (2H, d, J = 8.3 Hz), 6.64 (1H, d, J = 8.8 Hz), 6.73−6.79 (1H, m), 6.96 (2H, dd, J = 7.2 Hz), 7.30−7.33 (2H, m), 7.42−7.45 (2H, m), 9.82 (1H, br s). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 16.4 (d, $^3J_{CP}$ = 6.9 Hz), 18.8 (d, $^2J_{CP}$ = 8.1 Hz), 61.8 (d, $^2J_{CP}$ = 4.6 Hz), 68.1, 84.5, 88.7 (d, $^1J_{CP}$ = 182.3 Hz), 121.2, 121.9, 128.9, 129.2, 129.5, 134.9 (d, $^3J_{CP}$ = 17.3 Hz), 141.5, 159.0 (d, $^2J_{CP}$ = 10.4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 23.57 (m), 25.65 (M). IR (cm^{-1}) ν_{max}: 1020 (P−O), 1049 (P−O), 1242 (P═O), 1496, 1576, 1595, 2116, 2980, 3283. MS (ESI, pos) m/z: 370.3/371.3 (M + H^+, 100/23). HRMS: m/z calcd for $C_{21}H_{25}NO_3P$ (M + H)$^+$ 370.1567, found 370.1566. Chromatography: hexanes/EtOAc 8/2, R_f = 0.22.

*Diethyl (Z)-(1-(Benzylamino)-1-(4-fluorophenyl)pent-1-en-4-yn-2-yl)phosphonate (**5e**).* 1.12 g (3.08 mmol) of **2e**/**3e** was converted into **5e**. After column chromatography, 0.46 g of **5e** was obtained (1.14 mmol, 37% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.36 (6H, td, J = 7.1 Hz, $^4J_{HP}$ = 0.4 Hz), 1.85 (1H, t, J = 2.6 Hz), 2.61 (2H, dd, $^3J_{HP}$ = 16.4 Hz, J = 2.6 Hz), 3.91 (2H, d, J = 6.6 Hz), 4.06−4.15 (4H, m), 7.04−7.09 (4H, m), 7.19−7.26 (5H, m), 8.32 (1H, t, J = 6.6 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 16.3 (d, $^3J_{CP}$ = 7.0 Hz), 18.4 (d, $^2J_{CP}$ = 9.5 Hz), 48.4, 61.3 (d, $^2J_{CP}$ = 4.4 Hz), 67.2, 82.7 (d, $^1J_{CP}$ = 186.2 Hz), 84.5 (d, $^3J_{CP}$ = 1.5 Hz), 115.5 (d, $^2J_{CF}$ = 21.7 Hz), 126.9, 126.9, 128.4, 130.4 (d, $^3J_{CF}$ = 8.1 Hz), 130.6 (dd, $^3J_{CP}$ = 18.1 Hz, $^4J_{CF}$ = 3.2 Hz), 139.9, 162.8 (d, $^1J_{CF}$ = 248.3 Hz), 163.9 (d, $^2J_{CP}$ = 12.9 Hz). ^{19}F NMR (376 MHz, $CDCl_3$) δ: −114.48 to −114.41 (multiplet, m), −112.06 to −111.99 (multiplet, M). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 23.45 (m), 26.23 (M). IR (cm^{-1}) ν_{max}: 1022 (P−O), 1050 (P−O), 1205 (P═O), 1589, 1607, 2113, 2981, 3283. MS (ESI, pos) m/z: 402.1/403.1 (M + H^+, 100/23). HRMS: m/z calcd for $C_{22}H_{26}FNO_3P$ (M + H)$^+$ 402.1629, found 402.1628. Chromatography: hexanes/EtOAc 7/3, R_f = 0.29.

*Diethyl (Z)-(1-(Benzylamino)-1-(4-methoxyphenyl)pent-1-en-4-yn-2-yl)phosphonate (**5f**).* 1.0 g (2.67 mmol) of **2f**/**3f** was converted into **5f**. After column chromatography, 0.47 g of **5f** was obtained (1.14 mmol, 43% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.35 (6H, td, J = 7.1 Hz, $^4J_{HP}$ = 0.4 Hz), 1.86 (1H, t, J = 2.6 Hz), 2.66 (2H, dd, $^3J_{HP}$ = 16.5 Hz, J = 2.6 Hz), 3.84 (3H, s), 3.93 (2H, d, J = 6.5 Hz), 4.10 (4H, dq, $^3J_{HP}$ = 9.4 Hz, J = 7.2 Hz), 6.83−6.92 (2H, m), 7.09−7.25 (7H, m), 8.26 (1H, t, J = 6.5 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 16.3 (d, $^3J_{CP}$ = 7.1 Hz), 18.6 (d, $^2J_{CP}$ = 9.2 Hz), 48.5, 55.1, 61.1 (d, $^2J_{CP}$ = 4.3 Hz), 67.1, 82.1 (d, $^1J_{CP}$ = 185.6 Hz), 84.9 (d, $^3J_{CP}$ = 1.2 Hz), 113.8, 126.8, 126.8 (d, $^3J_{CP}$ = 17.7 Hz), 127.0, 128.3, 129.8, 140.1, 159.9, 164.9 (d, $^2J_{CP}$ = 12.8 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 23.91 (m), 26.82 (M). IR (cm^{-1}) ν_{max}: 1022 (P−O), 1050 (P−O), 1248 (P═O), 1592, 1610, 1712, 2116, 2980, 3287. MS (ESI, pos) m/z: 414.2/415.2 (M + H^+, 100/23). HRMS: m/z calcd for $C_{23}H_{29}NO_4P$ (M + H)$^+$ 414.1829, found 414.1842. Chromatography: hexanes/EtOAc 7/3, R_f = 0.21.

*Diethyl (Z)-(1-(Benzylamino)-1-phenylhex-1-en-4-yn-2-yl)phosphonate (**5h**).* 0.70 g (2.03 mmol) of **2a**/**3a** was converted into **5h**. After column chromatography, 0.37 g of **5h** was obtained (0.93 mmol, 46% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.36 (6H, td, J = 7.1 Hz, $^4J_{HP}$ = 0.4 Hz), 1.70 (3H, t, J = 2.5 Hz), 2.56 (2H, dq, $^3J_{HP}$ = 16.8 Hz, J = 2.5 Hz), 3.90 (2H, d, J = 6.5 Hz), 4.10 (4H, dq, $^3J_{HP}$ = 10.2 Hz, J = 7.1 Hz), 7.08−7.11 (2H, m), 7.19−7.25 (4H, m), 7.34−7.38 (4H, m), 8.25 (1H, t, J = 6.5 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 3.6, 16.3 (d, $^3J_{CP}$ = 7.1 Hz), 18.6 (d, $^2J_{CP}$ = 9.5 Hz), 48.5, 61.2 (d, $^2J_{CP}$ = 4.3 Hz), 73.9, 79.4 (d, $^3J_{CP}$ = 1.9 Hz), 82.9 (d, $^1J_{CP}$ = 184.3 Hz), 126.8, 127.0, 128.3, 128.5, 128.7, 134.9 (d, $^3J_{CP}$ = 17.9 Hz), 140.1, 164.6 (d, $^2J_{CP}$ = 12.9 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 24.27 (m), 27.17 (M). IR (cm^{-1}) ν_{max}: 1022 (P−O), 1051 (P−O), 1204 (P═O), 1590, 1606, 2238, 2918, 3266. MS (ESI, pos) m/z: 398.2/399.2 (M + H^+, 100/23). HRMS: m/z calcd for $C_{23}H_{29}NO_3P$ (M + H)$^+$ 398.1880, found 398.1887. Chromatography: hexanes/EtOAc 8/2, R_f = 0.29.

*Diethyl (Z)-(1-(Benzylamino)-5-(naphthalen-1-yl)-1-phenylpent-1-en-4-yn-2-yl)phosphonate (**5i**).* 0.70 g (2.03 mmol) of **2a**/**3a** was converted into **5i**. After column chromatography, 0.39 g of **5i** was obtained (0.77 mmol, 38% yield, pale yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.34 (6H, t, J = 7.1 Hz), 3.00 (2H, d, $^3J_{HP}$ = 16.4 Hz), 3.95 (2H, d, J = 6.4 Hz), 4.16 (4H, dq, $^3J_{HP}$ = 7.2 Hz, J = 7.1 Hz), 7.10−7.12 (2H, m), 7.17−7.20 (1H, m), 7.23−7.25 (1H, m), 7.32−7.37 (3H, m), 7.38−7.42 (4H, m), 7.49−7.53 (3H, m), 7.76 (1H, d, J = 8.3 Hz), 7.82−7.84 (1H, m), 8.21−8.24 (1H, m), 8.36 (1H, t, J = 6.4 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 16.5 (d, $^3J_{CP}$ = 7.0 Hz), 19.8 (d, $^2J_{CP}$ = 9.7 Hz), 48.6, 61.5 (d, $^2J_{CP}$ = 4.4 Hz), 77.4, 82.2 (d, $^1J_{CP}$ = 186.1 Hz), 95.8 (d, $^3J_{CP}$ = 1.6 Hz), 122.1, 125.4, 126.4, 126.5, 126.5, 130.0, 127.1, 127.9, 128.3, 128.5, 128.6, 128.6, 129.0, 129.8, 133.3, 133.7, 134.9 (d, $^3J_{CP}$ = 17.8 Hz), 140.2, 165.2 (d, $^2J_{CP}$ = 12.7 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 23.88 (m), 26.96 (M). IR (cm^{-1}) ν_{max}: 1022 (P−O), 1049 (P−O), 1205 (P═O), 1588, 1606, 2231, 2924, 3273. MS (ESI, pos) m/z: 510.2/511.2 (M + H^+, 100/30). HRMS: m/z calcd for $C_{32}H_{33}NO_3P$ (M + H)$^+$ 510.2193, found 510.2182. Chromatography: hexanes/EtOAc 8/2, R_f = 0.16.

*Diethyl (Z)-(1-(Benzylamino)-1-phenyl-5-(trimethylsilyl)pent-1-en-4-yn-2-yl)phosphonate (**5j**).* 0.70 g (2.03 mmol) of **2a**/**3a** was converted into **5j**. After column chromatography, 0.42 g of **5j** was obtained (0.91 mmol, 45% yield, yellow oil). However, **5j** and its bis-propargylated product constitute a chromatographically inseparable mixture. As a consequence, 20% of bis-propargylated product is present (^{31}P NMR (162 MHz, $CDCl_3$) δ: 25.61 ppm). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.10 (9H, s), 1.36 (6H, td, J = 7.1 Hz, $^4J_{HP}$ = 0.3 Hz), 2.63 (2H, d, J = 16.3 Hz), 3.91 (2H, d, J = 6.5 Hz), 4.11 (4H, dq, $^3J_{HP}$ = 7.4 Hz, J = 7.1 Hz), 7.09−7.11 (2H, m), 7.19−7.30 (4H, m), 7.33−7.38 (4H, m), 8.28 (1H, t, J = 6.5 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 0.1, 16.4 (d, $^3J_{CP}$ = 7.2 Hz), 19.7 (d, $^2J_{CP}$ = 9.7 Hz), 48.5, 61.2 (d, $^2J_{CP}$ = 4.2 Hz), 82.0 (d, $^1J_{CP}$ = 185.7 Hz), 82.7, 87.1 (d, $^3J_{CP}$ = 1.3 Hz), 126.8, 127.0, 127.6, 128.1, 128.3, 128.3, 128.6, 128.8, 134.7 (d, $^3J_{CP}$ = 17.7 Hz), 140.1, 165.1 (d, $^2J_{CP}$ = 12.7 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 23.74 (m), 26.83 (M). IR (cm^{-1}) ν_{max}: 1024 (P−O), 1051 (P−O), 1248 (P═O), 1590, 1607, 2172, 2959, 3267. MS (ESI, pos) m/z: 456.2/457.2 (M + H^+, 100/30). HRMS: m/z calcd for $C_{25}H_{35}NO_3PSi$ (M + H)$^+$ 456.2118, found 456.2121. Chromatography: hexanes/EtOAc 7/3, R_f = 0.19.

Synthesis of Pyrroles 6a−g. Propargylic enaminophosphonates **5a−g** were dissolved in CH_3CN (0.5 mmol/mL) in a round-bottom flask, and 5 mol % of $ZnCl_2$ was added. The reaction progress was monitored using HPLC. When all starting material had been consumed, the reaction mixture was filtered over a plug of silica (ca. 5 cm) to remove the catalyst. If necessary, column chromatography was performed.

Synthesis of Pyrroles 6h−i. Propargylic enaminophosphonates **5h−i** were dissolved in dry CH_3CN (0.5 mmol/mL) in a round-bottom flask, and 20 mol % of dried $ZnCl_2$ (2 h at 60 °C under a 1 mbar vacuum) was added. The mixture was then heated to reflux temperature. The reaction progress was monitored using HPLC. When all starting material had been consumed, the reaction mixture was filtered over a plug of silica (ca. 5 cm) to remove the catalyst. If necessary, column chromatography was performed.

*Diethyl (1-Benzyl-5-methyl-2-phenyl-1H-pyrrol-3-yl)phosphonate (**6a**).* 51 mg (0.13 mmol) of **5a** was converted into 50 mg of **6a** (0.13 mmol, 99% yield, yellow oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 1.12 (6H, t, J = 6.9 Hz), 2.11 (3H, s), 3.81−4.03 (4H, m), 4.96 (2H, s), 6.40 (1H, d, $^3J_{HP}$ = 4.4 Hz), 6.83−6.85 (2H, m), 7.19−7.37 (8H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 12.5, 16.2 (d, $^3J_{CP}$ = 6.9 Hz), 47.9, 61.4 (d, $^2J_{CP}$ = 5.8 Hz), 106.5 (d, $^1J_{CP}$ = 218.1 Hz), 111.7 (d, $^2J_{CP}$ = 11.5 Hz), 125.7, 127.3, 128.0, 128.4, 128.8, 130.0 (d, $^3J_{CP}$ = 15.0 Hz), 130.8, 131.9, 137.9, 139.3 (d, $^2J_{CP}$ = 23.1 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 18.89. IR (cm^{-1}) ν_{max}: 1024 (P−O), 1053 (P−O), 1227 (P═O), 1400, 1454, 2979. MS (ESI, pos) m/z: 384.3/385.3 (M + H^+, 100/15). HRMS: m/z calcd for $C_{22}H_{27}NO_3P$ (M + H)$^+$ 384.1723, found 384.1719.

*Diethyl (1-Allyl-5-methyl-2-phenyl-1H-pyrrol-3-yl)phosphonate (**6b**).* 80 mg (0.24 mmol) of **5b** was converted into 71 mg of **6b** (0.21 mmol, 89% yield, yellow oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 1.10 (6H, t, J = 7.2 Hz), 2.23 (3H, s), 3.79−4.01 (4H, m), 4.29 (2H, m), 4.76 (1H, d, J_E = 16.8 Hz), 5.15 (1H, d, J_Z = 10.6 Hz), 5.80 (1H, ddt, J_E = 16.8 Hz, J_Z = 10.6 Hz, J = 4.5 Hz), 6.36 (1H, d, $^3J_{HP}$ = 4.4 Hz), 7.38 (5H, s). ^{13}C

dx.doi.org/10.1021/jo500139z | J. Org. Chem. 2014, 79, 4322−4331

NMR (75 MHz, $CDCl_3$) δ: 12.2, 16.2 (d, $^3J_{CP}$ = 6.9 Hz), 46.7, 61.5 (d, $^2J_{CP}$ = 5.8 Hz), 105.8 (d, $^1J_{CP}$ = 219.2 Hz), 111.3 (d, $^2J_{CP}$ = 11.5 Hz), 116.3, 127.9, 128.5, 129.9 (d, $^3J_{CP}$ = 16.1 Hz), 130.7, 131.9, 133.9, 138.9 (d, $^2J_{CP}$ = 24.2 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 18.99. IR (cm^{-1}) ν_{max}: 1024 (P−O), 1054 (P−O), 1235 (P═O), 1399, 1475, 2979. MS (ESI, pos) *m/z*: 334.3/335.3 ($M + H^+$, 100/17). HRMS: *m/z* calcd for $C_{18}H_{25}NO_3P$ $(M + H)^+$ 334.1567, found 334.1566.

*Diethyl (1-Butyl-5-methyl-2-phenyl-1H-pyrrol-3-yl)phosphonate (**6c**).* 100 mg (0.29 mmol) of **5c** was converted into 95 mg of **6c** (0.27 mmol, 94% yield, yellow oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 0.74 (3H, t, *J* = 7.6 Hz), 1.07−1.16 (8H, m), 1.45 (2H, quint, *J* = 7.6 Hz), 2.27 (3H, s), 3.69 (2H, t, *J* = 7.6 Hz), 3.78−4.01 (4H, m), 6.32 (1H, d, $^3J_{HP}$ = 3.9 Hz), 7.38 (5H, s). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 12.5, 13.5, 16.1 (d, $^3J_{CP}$ = 6.9 Hz), 19.8, 32.9, 44.2, 61.5 (d, $^2J_{CP}$ = 4.6 Hz), 105.4 (d, $^1J_{CP}$ = 218.1 Hz), 111.3 (d, $^2J_{CP}$ = 12.7 Hz), 128.0, 128.3, 129.3 (d, $^3J_{CP}$ = 16.2 Hz), 130.9, 132.3, 138.7 (d, $^2J_{CP}$ = 24.2 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 19.21. IR (cm^{-1}) ν_{max}: 1024 (P−O), 1054 (P−O), 1227 (P═O), 1400, 1475, 2931, 2959. MS (ESI, pos) *m/z*: 350.3/351.3 ($M + H^+$, 100/13). HRMS: *m/z* calcd for $C_{19}H_{29}NO_3P$ $(M + H)^+$ 350.1880, found 350.1885.

*Diethyl (5-Methyl-1,2-diphenyl-1H-pyrrol-3-yl)phosphonate (**6d**).* 75 mg (0.20 mmol) of **5d** was converted into 68 mg of **6d** (0.18 mmol, 91% yield, yellow oil). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 1.12 (6H, t, *J* = 6.9 Hz), 2.10 (3H, s), 3.84−4.06 (4H, m), 6.44 (1H, d, $^3J_{HP}$ = 4.4 Hz), 7.03−7.06 (2H, m), 7.14−7.23 (5H, m), 7.27−7.31 (3H, m). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 13.1, 16.2 (d, $^3J_{CP}$ = 6.9 Hz), 61.5 (d, $^2J_{CP}$ = 5.8 Hz), 106.9 (d, $^1J_{CP}$ = 218.1 Hz), 111.7 (d, $^2J_{CP}$ = 11.5 Hz), 127.5, 127.5, 128.0, 128.5, 129.0, 130.9, 131.2, 131.8, 138.1, 139.0 (d, $^2J_{CP}$ = 24.2 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ: 18.81. IR (cm^{-1}) ν_{max}: 1023 (P−O), 1053 (P−O), 1238 (P═O), 1391, 1496, 2979. MS (ESI, pos) *m/z*: 370.1/371.2 ($M + H^+$, 100/18). HRMS: *m/z* calcd for $C_{21}H_{25}NO_3P$ $(M + H)^+$ 370.1567, found 370.1570.

*Diethyl (1-Benzyl-2-(4-fluorophenyl)-5-methyl-1H-pyrrol-3-yl)-phosphonate (**6e**).* 100 mg (0.25 mmol) of **5e** was converted into 97 mg of **6e** (0.24 mmol, 97% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.15 (6H, t, *J* = 7.1 Hz), 2.12 (3H, s), 3.87−3.98 (4H, m), 4.92 (2H, s), 6.39 (1H, d, $^3J_{HP}$ = 3.7 Hz), 6.81−6.83 (2H, m), 6.79−7.02 (2H, m), 7.21−7.30 (5H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 12.4, 16.2 (d, $^3J_{CP}$ = 6.9 Hz), 47.8, 61.4, 106.7 (d, $^1J_{CP}$ = 209.0 Hz), 111.5 (d, $^2J_{CP}$ = 12.0 Hz), 114.9 (d, $^2J_{CF}$ = 21.5 Hz), 125.5, 127.3, 127.7 (d, $^4J_{CF}$ = 3.44 Hz), 128.8, 130.1 (d, $^3J_{CP}$ = 15.5 Hz), 132.6 (d, $^3J_{CF}$ = 8.5 Hz), 137.6, 138.1 (d, $^2J_{CP}$ = 23.4 Hz), 162.8 (d, $^1J_{CF}$ = 248.1 Hz). ^{19}F NMR (376 MHz, $CDCl_3$) δ: −113.01. ^{31}P NMR (162 MHz, $CDCl_3$) δ: 17.92. IR (cm^{-1}) ν_{max}: 1025 (P−O), 1053 (P−O), 1223 (P═O), 1392, 1480, 1529, 2981. MS (ESI, pos) *m/z*: 402.2/403.2 ($M + H^+$, 100/25). HRMS: *m/z* calcd for $C_{22}H_{26}FNO_3P$ $(M + H)^+$ 402.1629, found 402.1635.

*Diethyl (1-Benzyl-2-(4-methoxyphenyl)-5-methyl-1H-pyrrol-3-yl)-phosphonate (**6f**).* 98 mg (0.24 mmol) of **5f** was converted into **6f**. After preparative TLC, 71 mg of **6f** was obtained (0.17 mmol, 72% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.15 (6H, td, *J* = 7.1 Hz, $^4J_{HP}$ = 0.4 Hz), 2.10 (3H, s), 3.79 (3H, s), 3.83−4.02 (4H, m), 4.94 (2H, s), 6.37 (1H, dd, $^3J_{HP}$ = 4.5 Hz, *J* = 0.9 Hz), 6.82−6.85 (4H, m), 7.21−7.28 (5H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 12.4, 16.2 (d, $^3J_{CP}$ = 7.2 Hz), 47.7, 55.2, 61.3 (d, $^2J_{CP}$ = 5.3 Hz), 106.1 (d, $^1J_{CP}$ = 218.0 Hz), 111.4 (d, $^2J_{CP}$ = 11.9 Hz), 113.3, 123.9, 125.6, 127.2, 128.7, 129.7 (d, $^3J_{CP}$ = 15.5 Hz), 131.9, 137.9, 139.2 (d, $^2J_{CP}$ = 23.5 Hz), 159.6. ^{31}P NMR (162 MHz, $CDCl_3$) δ: 18.45. IR (cm^{-1}) ν_{max}: 1025 (P−O), 1053 (P−O), 1245 (P═O), 1395, 1481, 1531, 2979. MS (ESI, pos) *m/z*: 414.2/415.2 ($M + H^+$, 100/25). HRMS: *m/z* calcd for $C_{23}H_{29}NO_4P$ $(M + H)^+$ 414.1829, found 414.1838. Preparative TLC: EtOAc, R_f = 0.50.

*Diethyl (1-Benzyl-2,5-dimethyl-1H-pyrrol-3-yl)phosphonate (**6g**).* 100 mg of crude **5g** was converted into **6g**. After preparative TLC, 10 mg of **6g** was obtained (0.03 mmol, 10% yield over two steps, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.32 (6H, td, *J* = 7.1 Hz, $^4J_{HP}$ = 0.4 Hz), 2.11 (3H, br s), 2.37 (3H, d, $^3J_{HP}$ = 1.8 Hz), 3.99−4.16 (4H, m), 5.03 (2H, s), 6.14 (1H, dq, $^3J_{HP}$ = 4.2 Hz, *J* = 1.0 Hz), 6.86−6.88 (2H, m), 7.25−7.33 (3H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 11.6, 12.2 (d, $^3J_{CP}$ = 1.0 Hz), 16.4 (d, $^3J_{CP}$ = 6.8 Hz), 47.0 (d, $^4J_{CP}$ = 1.5 Hz), 61.3 (d, $^2J_{CP}$ = 5.0 Hz), 103.6 (d, $^1J_{CP}$ = 216.9 Hz), 109.6 (d, $^2J_{CP}$ = 11.9 Hz), 125.6, 127.4, 128.9, 129.1 (d, $^3J_{CP}$ = 15.3 Hz), 136.3 (d, $^2J_{CP}$ = 24.2 Hz), 137.0. ^{31}P NMR (162 MHz, $CDCl_3$) δ: 19.77. IR (cm^{-1}) ν_{max}: 1025 (P−O), 1076 (P−O), 1230 (P═O), 1410, 1519, 2980. MS (ESI, pos) *m/z*: 322.1/323.1 ($M + H^+$, 100/15). HRMS: *m/z* calcd for $C_{17}H_{25}NO_3P$ $(M + H)^+$ 322.1567, found 322.1575. Preparative TLC: EtOAc, R_f = 0.47.

*Diethyl (1-Benzyl-5-ethyl-2-phenyl-1H-pyrrol-3-yl)phosphonate (**6h**).* 140 mg (0.35 mmol) of **5h** was converted into **6h**. After preparative TLC, 63 mg of **6h** was obtained (0.16 mmol, 46% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.11 (6H, td, *J* = 7.1 Hz, $^4J_{HP}$ = 0.4 Hz), 1.22 (3H, t, *J* = 7.5 Hz), 2.40 (2H, q, *J* = 7.5 Hz), 3.82−4.01 (4H, m), 4.96 (2H, s), 6.44 (1H, dt, $^3J_{HP}$ = 4.7 Hz, *J* = 1.0 Hz), 6.83 (2H, d, *J* = 8.0 Hz), 7.22−7.27 (4H, m), 7.29−7.33 (4H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 12.0, 16.1 (d, $^3J_{CP}$ = 7.1 Hz), 19.7, 47.7, 61.3 (d, $^2J_{CP}$ = 5.3 Hz), 106.3 (d, $^1J_{CP}$ = 218.1 Hz), 109.7 (d, $^2J_{CP}$ = 12.3 Hz), 125.6, 127.2, 127.9, 128.4, 128.7, 130.8, 131.7, 136.1 (d, $^3J_{CP}$ = 15.0 Hz), 137.9, 139.1 (d, $^2J_{CP}$ = 23.2 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 18.53. IR (cm^{-1}) ν_{max}: 1023 (P−O), 1053 (P−O), 1229 (P═O), 1390, 2976. MS (ESI, pos) *m/z*: 398.2/399.2 ($M + H^+$, 100/25). HRMS: *m/z* calcd for $C_{23}H_{29}NO_3P$ $(M + H)^+$ 398.1880, found 398.1884. Preparative TLC: EtOAc, R_f = 0.55.

*Diethyl (1-Benzyl-5-(naphthalen-1-ylmethyl)-2-phenyl-1H-pyrrol-3-yl)phosphonate (**6i**).* 0.30 g (0.59 mmol) of **5i** was converted into **6i**. After column chromatography, 0.11 g of **6i** was obtained (0.22 mmol, 37% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 1.06 (6H, t, *J* = 6.8 Hz), 3.78−3.96 (4H, m), 4.16 (2H, s), 4.98 (2H, s), 6.17 (1H, d, $^3J_{HP}$ = 4.5 Hz), 6.87 (2H, d, *J* = 7.4 Hz), 7.17 (1H, d, *J* = 7.0 Hz), 7.25−7.47 (11H, m), 7.69 (1H, d, *J* = 8.4 Hz), 7.75 (1H, d, *J* = 8.2 Hz), 7.84 (1H, d, *J* = 8.1 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 16.1 (d, $^3J_{CP}$ = 7.0 Hz), 30.3, 48.1, 61.3 (d, $^2J_{CP}$ = 5.4 Hz), 106.9 (d, $^1J_{CP}$ = 218.2 Hz), 113.3 (d, $^2J_{CP}$ = 12.3 Hz), 123.8, 125.6, 125.7, 125.8, 126.0, 126.7, 127.5, 128.0, 128.5, 128.7, 128.8, 130.8, 131.6, 132.0, 132.3 (d, $^3J_{CP}$ = 15.4 Hz), 133.9, 134.1, 137.8, 139.9 (d, $^2J_{CP}$ = 23.4 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 18.06. IR (cm^{-1}) ν_{max}: 1027 (P−O), 1055 (P−O), 1236 (P═O), 1453, 2928. MS (ESI, pos) *m/z*: 510.2/511.3 ($M + H^+$, 100/35). HRMS: *m/z* calcd for $C_{32}H_{33}NO_3P$ $(M + H)^+$ 510.2193, found 510.2215. Chromatography: hexanes/EtOAc 1/1, R_f = 0.41.

Synthesis of Pyrrole 8. In a round-bottom flask, pyrrole **6c** was dissolved in a 2/1 1,4-dioxane/acetic acid mixture (0.5 mmol/mL). *N*-Bromosuccinimide (NBS, 1.05 equiv) was added, and the reaction mixture was stirred for 30 min at 20 °C. The reaction mixture was poured into a 2 N NaOH solution (10 mL) and extracted with diethyl ether (3 × 10 mL). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated in vacuo.

*Diethyl (4-Bromo-1-butyl-5-methyl-2-phenyl-1H-pyrrol-3-yl)-phosphonate (**8**).* 100 mg (0.29 mmol) of **6c** was converted into 99 mg of **8** (0.27 mmol, 92% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.74 (3H, t, *J* = 7.3 Hz), 1.06−1.15 (8H, m), 1.39−1.46 (2H, m), 2.28 (3H, d, $^5J_{HP}$ = 0.4 Hz), 3.60−3.64 (2H, m), 3.78−3.87 (2H, m), 3.92−4.01 (2H, m), 7.30−7.33 (2H, m), 7.38−7.41 (3H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 11.1, 13.4, 16.1 (d, $^3J_{CP}$ = 7.0 Hz), 19.7, 32.7, 45.0, 61.4 (d, $^2J_{CP}$ = 5.6 Hz), 97.9 (d, $^2J_{CP}$ = 8.4 Hz), 106.3 (d, $^1J_{CP}$ = 223.1 Hz), 127.9, 128.2 (d, $^3J_{CP}$ = 12.6 Hz), 128.6, 131.1, 131.9, 139.7 (d, $^2J_{CP}$ = 21.0 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 14.12. IR (cm^{-1}) ν_{max}: 1024 (P−O), 1057 (P−O), 1243 (P═O), 1391, 1469, 2960. MS (ESI, pos) *m/z*: 428.1/430.1 ($M + H^+$, 98/100). HRMS: *m/z* calcd for $C_{19}H_{28}BrNO_3P$ $(M + H)^+$ 428.0985, found 428.0991.

Synthesis of Pyrrole 9a. In a round-bottom flask, pyrrole **6c** was dissolved in dry THF (0.5 mmol/mL) under an inert N_2 atmosphere and cooled to −78 °C. A solution of *s*-BuLi (1.2 equiv) was added in a dropwise fashion and the reaction mixture kept at −78 °C for 1 h. Next, an excess of D_2O was added, and the mixture was allowed to warm to room temperature after which it was extracted with diethyl ether (3 × 10 mL). The combined organic layers were dried over $MgSO_4$, filtered and concentrated in vacuo. The crude residue was purified using preparative TLC.

*Diethyl (1-Butyl-5-methyl-2-phenyl-1H-pyrrol-3-yl-4-d)phosphonate (**9a**).* 127 mg (0.36 mmol) of **6c** was converted into **9a**. After preparative TLC, 72 mg of **9a** was obtained (0.21 mmol, 57% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.75 (3H, t, *J* = 7.4 Hz), 1.07−1.16 (8H, m), 1.41−1.49 (2H, m), 2.27 (3H, s), 3.67 (1H, d, *J* =

dx.doi.org/10.1021/jo500139z | J. Org. Chem. 2014, 79, 4322−4331

7.8 Hz), 3.69 (1H, d, J = 7.8 Hz), 3.78−3.97 (4H, m), 7.36−7.40 (5H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 12.4 (d, $^4J_{CP}$ = 1.1 Hz), 13.5, 16.0 (d, $^3J_{CP}$ = 7.2 Hz), 19.7, 32.8, 44.1, 61.2 (d, $^2J_{CP}$ = 5.5 Hz), 105.6 (d, $^1J_{CP}$ = 218.6 Hz), 110.9 (td, $^1J_{DC}$ = 25.2 Hz, $^2J_{CP}$ = 13.3 Hz), 127.9, 128.2, 129.1 (d, $^3J_{CP}$ = 15.7 Hz), 130.9, 132.3, 138.5 (d, $^2J_{CP}$ = 23.3 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 18.45. IR (cm^{-1}) ν_{max}: 1026 (P−O), 1055 (P−O), 1229 (P═O), 1392, 1474, 2960. MS (ESI, pos) m/z: 351.3/352.3 (M + H$^+$, 100/15). HRMS: m/z calcd for $C_{19}H_{28}DNO_3P$ (M + H)$^+$ 351.1942, found 351.1946. Preparative TLC: EtOAc, R_f = 0.41.

Synthesis of Pyrrole 9b. In a round-bottom flask, pyrrole **6c** was dissolved in dry THF (1 mmol/mL) under an inert N_2-atmosphere and cooled to −78 °C. A solution of *s*-BuLi (1.2 equiv) was added in a dropwise fashion and the reaction mixture kept at −78 °C for 1 h. Next, iodomethane (1.1 equiv) was added, and the mixture was allowed to warm to room temperature after which it was extracted with diethyl ether (3 × 10 mL). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated in vacuo. The residue was purified using column chromatography.

*Diethyl (1-Butyl-4,5-dimethyl-2-phenyl-1H-pyrrol-3-yl)phosphonate (**9b**).* 0.86 g (2.45 mmol) of **6c** was converted into **9b**. After column chromatography, 0.23 g of **9b** was obtained (0.64 mmol, 26% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.74 (3H, t, J = 7.3 Hz), 1.07−1.13 (8H, m), 1.38−1.46 (2H, m), 2.18 (3H, s), 2.22 (3H, s), 3.57 (1H, d, J = 7.9 Hz), 3.59 (1H, d, J = 7.9 Hz), 3.72−3.82 (2H, m), 3.86−3.95 (2H, m), 7.31−7.38 (5H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 9.9 (d, $^3J_{CP}$ = 1.4 Hz), 10.8, 13.0, 16.0 (d, $^3J_{CP}$ = 7.1 Hz), 19.7, 32.9, 44.0, 60.7 (d, $^2J_{CP}$ = 5.3 Hz), 105.1 (d, $^1J_{CP}$ = 215.2 Hz), 117.9 (d, $^2J_{CP}$ = 13.0 Hz), 126.0 (d, $^3J_{CP}$ = 16.1 Hz), 127.6, 128.0, 131.1, 132.8, 138.4 (d, $^2J_{CP}$ = 23.6 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 18.56. IR (cm^{-1}) ν_{max}: 1026 (P−O), 1056 (P−O), 1230 (P═O), 1246, 1393, 2930. MS (ESI, pos) m/z: 364.2/365.2 (M + H$^+$, 100/22). HRMS: m/z calcd for $C_{20}H_{31}NO_3P$ (M + H)$^+$ 364.2036, found 364.2047. Chromatography: EtOAc/hexanes 3/2, R_f = 0.15.

Synthesis of Pyrrole 11m. In a 10 mL Pyrex microwave vial equipped with a "snap-cap" and magnetic stirrer, pyrrole **8** was dissolved in a 3/1 DME/H_2O mixture. $PhB(OH)_2$ (1.3 equiv) was added, along with Na_2CO_3 (2 equiv) and $Pd(PPh_3)_4$ (5 mol %). The vial was inserted into the microwave, and the reaction was performed at 130 °C during 1 h. Afterward, the reaction mixture was poured into water (10 mL) and extracted with diethyl ether (3 × 10 mL). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated in vacuo. The crude product was purified using preparative TLC.

*Diethyl (1-Butyl-5-methyl-2,4-diphenyl-1H-pyrrol-3-yl)phosphonate (**11m**).* 96 mg (0.22 mmol) of **8** was converted into **11m**. After preparative TLC, 52 mg of **11m** was obtained (0.12 mmol, 63% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.75−0.80 (9H, m), 1.15 (2H, sext, J = 7.4 Hz), 1.46−1.54 (2H, m), 2.20 (3H, s), 3.41−3.51 (2H, m), 3.59−3.70 (4H, m), 7.23−7.28 (1H, m), 7.34−7.48 (9H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 10.7 (d, $^4J_{CP}$ = 1.2 Hz), 13.5, 15.7 (d, $^3J_{CP}$ = 7.3 Hz), 19.9, 32.9, 44.4, 60.8 (d, $^2J_{CP}$ = 6.0 Hz), 106.0 (d, $^1J_{CP}$ = 217.6 Hz), 124.6 (d, $^2J_{CP}$ = 12.0 Hz), 126.2, 126.9 (d, $^3J_{CP}$ = 15.0 Hz), 127.6, 127.8, 128.2, 130.8, 131.2, 132.9, 136.1, 139.0 (d, $^2J_{CP}$ = 22.9 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 17.30. IR (cm^{-1}) ν_{max}: 1029 (P−O), 1057 (P−O), 1228 (P═O), 1248, 1392, 2960. MS (ESI, pos) m/z: 426.2/427.2 (M + H$^+$, 100/22). HRMS: m/z calcd for $C_{25}H_{33}NO_3P$ (M + H)$^+$ 426.2193, found 426.2195.

Synthesis of Pyrrole 11o. In a 10 mL Pyrex microwave vial equipped with a "snap-cap" and magnetic stirrer, pyrrole **8** was dissolved in DMF. Allyltributyltin (3.0 equiv) was added, along with $Pd(PPh_3)_4$ (5 mol %). The vial was inserted into the microwave, and the reaction was performed at 130 °C during 3 h. Afterward, the reaction mixture was poured into brine (10 mL) and extracted with diethyl ether (3 × 10 mL). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated in vacuo. The crude product was purified using column chromatography.

*Diethyl (4-Allyl-1-butyl-5-methyl-2-phenyl-1H-pyrrol-3-yl)phosphonate (**11o**).* 80 mg (0.19 mmol) of **8** was converted into **11o**. After column chromatography, 32 mg of **11o** was obtained (0.08 mmol, 43% yield, yellow oil). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.74 (3H, t, J = 7.4 Hz), 1.06−1.13 (8H, m), 1.39−1.43 (2H, m), 2.17 (3H, s), 3.48 (2H, d, J = 6.2 Hz), 3.57−3.61 (2H, m), 3.72−3.79 (2H, m), 3.86−3.92 (2H, m), 4.95 (1H, ddd, J_Z = 10.1 Hz, J = 3.5 Hz, J = 1.6 Hz), 5.00 (1H, ddd, J_E = 17.0 Hz, J = 3.8 Hz, J = 1.6 Hz), 5.99 (1H, ddt, J_E = 17.0 Hz, J_Z = 10.1 Hz, J = 6.2 Hz), 7.31−7.34 (2H, m), 7.36−7.39 (3H, m). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 10.1 (d, $^4J_{CP}$ 1.5 Hz), 13.5, 16.1 (d, $^3J_{CP}$ = 7.2 Hz), 19.8, 29.9, 32.9, 44.1, 60.8 (d, $^2J_{CP}$ = 5.4 Hz), 104.7 (d, $^1J_{CP}$ = 215.9 Hz), 113.5, 120.3 (d, $^2J_{CP}$ = 13.5 Hz), 126.9 (d, $^3J_{CP}$ = 16.1 Hz), 127.6, 128.1, 131.2, 132.9, 138.4, 138.4 (d, $^2J_{CP}$ = 23.0 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ: 18.23. IR (cm^{-1}) ν_{max}: 1028 (P−O), 1056 (P−O), 1225 (P═O), 1246, 1395, 1466, 2929. MS (ESI, pos) m/z: 390.2/391.2 (M + H$^+$, 100/22). HRMS: m/z calcd for $C_{22}H_{33}NO_3P$ (M + H)$^+$ 390.2193, found 390.2205.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H, ^{13}C, ^{31}P NMR spectra and LC traces of new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the Research Foundation Flanders (FWO) for financial support for pre- and postdoctoral mandates.

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