Advanced Synthesis & Catalysis

DOI: 10.1002/adsc.201400497

Metal-Free Regioselective β-Alkylation of Pyrroles with Carbonyl Compounds and Hydrosilanes: Use of a Brønsted Acid as a Catalyst

Shota Nomiyama[a] and Teruhisa Tsuchimoto[a,*]

[a] Department of Applied Chemistry, School of Science and Technology, Meiji University, 1-1-1 Higashimita, Tama-ku, Kawasaki 214-8571, Japan
Fax: (+81)-44-934-7228; e-mail: tsuchimo@meiji.ac.jp

Received: May 19, 2014; Revised: August 18, 2014; Published online: ■■ ■■, 0000

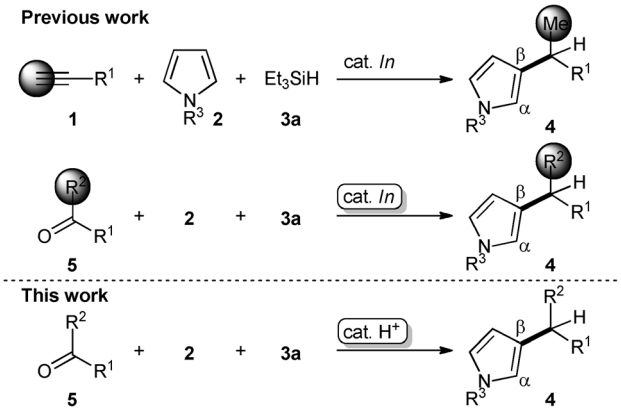
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201400497.

Abstract: A Brønsted acid, trifluoromethanesulfonimide [$HN(SO_2CF_3)_2$], was found to catalyze reductive β-alkylation of pyrroles with carbonyl compounds and hydrosilanes. This metal-free process features lower catalyst loadings compared to the original indium variant and exclusive generation of β-alkylpyrroles.

Keywords: alkylation; Brønsted acids; heterocycles; hydrides; regioselectivity

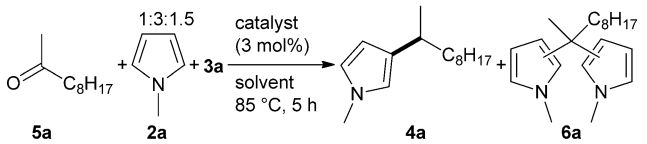
β-Alkylpyrroles are key structural motifs in natural products and biologically active compounds[1] as well as functional materials.[2] Due to sufficient aromaticity and π-excessive nature of pyrroles, a straightforward approach to β-alkylpyrroles seems to be S_EAr-based direct introduction of an alkyl group onto the pyrrole ring.[3] However, preferential α-nucleophilicity of pyrroles actually makes the β-alkylation considerably difficult.[4,5,6] Despite such characteristics of pyrroles, we have recently achieved S_EAr-based regioselective β-alkylation of pyrroles by simply mixing alkynes **1**, pyrroles **2** and Et_3SiH (**3a**) under indium catalysis (Scheme 1).[7] This was the first example of the S_EAr-based β-alkylation of pyrroles performed in one-step and catalytically. However, the alkyl unit installable onto **2** was restricted to the secondary alkyl group with a methyl substituent since **1** has been limited mainly to terminal alkynes. We therefore improved the issue by replacing **1** with carbonyl compounds **5**, which serve as a source of a broad range of alkyl groups including primary, secondary and tertiary as well as cyclic structures.[8] In addition to the improvement, we envisaged that exploiting a new catalyst in lieu of the indium salt, which includes a rather expensive indium metal[9] and is required to be pre-synthesized,[10,11] would further enhance the practicality and utility of the strategy. In terms of the social requirements of sustainable development, we aimed at achieving the β-alkylation as a metal-free process. We now report details of more sophisticated β-alkylation of pyrroles, where a Brønsted acid as a commercial source shows outstanding catalytic performance.

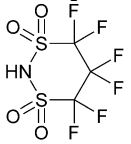
We first examined the effect of Brønsted acid catalysts in the reaction of *N*-methylpyrrole (**2a**) with 2-decanone (**5a**) and Et_3SiH (**3a**) under the conditions in 1,4-dioxane at 85 °C for 5 h (Table 1). Despite that $HNTf_2$ (25 mol%, $Tf = SO_2CF_3$) was totally inactive in the preceding study with the corresponding alkyne (1-decyne),[7] 3 mol% of $HNTf_2$ successfully catalyzed the reaction of **5a**, giving 3-(decan-2-yl)-1-methylpyrrole (**4a**) as a single isomer in 91% yield (entry 1). The non-formation of its α-isomer and complete consumption of dipyrrolylalkanes **6a** as plausible intermediates are noteworthy. Although using other sulfonimides as well as oxygen and carbon analogues of $HNTf_2$ resulted in a complete conversion of **5a**, a significant amount of **6a** remained unconsumed (entries 2–6). In addition to CF_3COOH, inorganic



Scheme 1. Catalytic reductive β-alkylation of pyrroles.

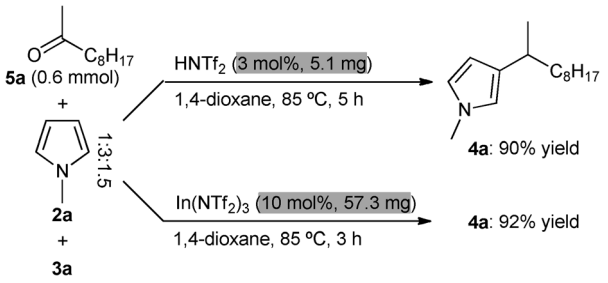
Table 1. Brønsted acid-catalyzed reductive β-2-decylation of **2a**.[a]



Entry	Catalyst	Solvent	Conv. (%)[b] 5a	Yield (%)[c] 4a	6a
1	$HNTf_2$	1,4-dioxane	>99	91	<1
2	$HNNf_2$[d]	1,4-dioxane	>99	79	8
3		1,4-dioxane	>99	62	21
4	HOTf	1,4-dioxane	>99	15	50
5	HONf[d]	1,4-dioxane	>99	12	51
6	$HCTf_2(C_6F_5)$	1,4-dioxane	>99	66	25
7	CF_3COOH	1,4-dioxane	<1	<1	<1
8	HBF_4 aq.	1,4-dioxane	74	5	49
9	H_2SO_4	1,4-dioxane	21	<1	5
10	HNO_3	1,4-dioxane	<1	<1	<1
11	$HNTf_2$	Bu_2O	93	19	<1
12	$HNTf_2$	PhMe	96	46	<1
13	$HNTf_2$	PhCl	>99	69	10
14	$HNTf_2$	$MeNO_2$	83	61	<1
15	$HNTf_2$	EtCN	>99	88	<1
16	$HNTf_2$	DMF[e]	<1	<1	<1
17[f]	$HNTf_2$	1,4-dioxane	>99	87	<1
18[g]	$HNTf_2$	1,4-dioxane	98	84	<1
19[h]	$HNTf_2$	1,4-dioxane	>99	76	<1

[a] Reagents: **5a** (0.60 mmol), **2a** (1.8 mmol), **3a** (0.90 mmol), catalyst (18 μmol), solvent (0.60 mL).
[b] Determined by GC.
[c] Determined by ^1H NMR.
[d] Nf = $SO_2C_4F_9$.
[e] DMF = *N*,*N*-dimethylformamide.
[f] Performed with **2a** (1.2 mmol).
[g] Performed with **2a** (0.60 mmol).
[h] Performed with **2a** (0.60 mmol) and **3a** (0.60 mmol).

Brønsted acids such as HBF_4, H_2SO_4 and HNO_3 were much less effective (entries 7–10). With $HNTf_2$ as a promising catalyst, the continuous survey of the solvent effect showed that 1,4-dioxane is the solvent of choice for the reaction (entries 1 and 11–16). The effect of the amounts of **2a** and **3a** was also examined. Reducing the amount of **2a** from 3 to 2 and 1 molar equivalents to **5a** lowered the yield of **4a** but not significantly (entries 17 and 18). Accordingly, in the case that pyrrole substrates are expensive and elaborate, the use of less than 3 molar equivalents of the pyrrole should be a possible choice of the reaction conditions. On the other hand, reducing the quantity of both **2a** and **3a** resulted in further decrease of the yield (entry 19).

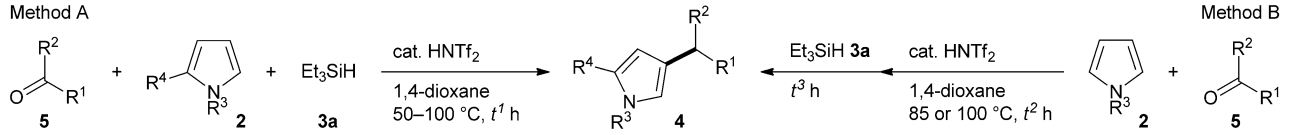


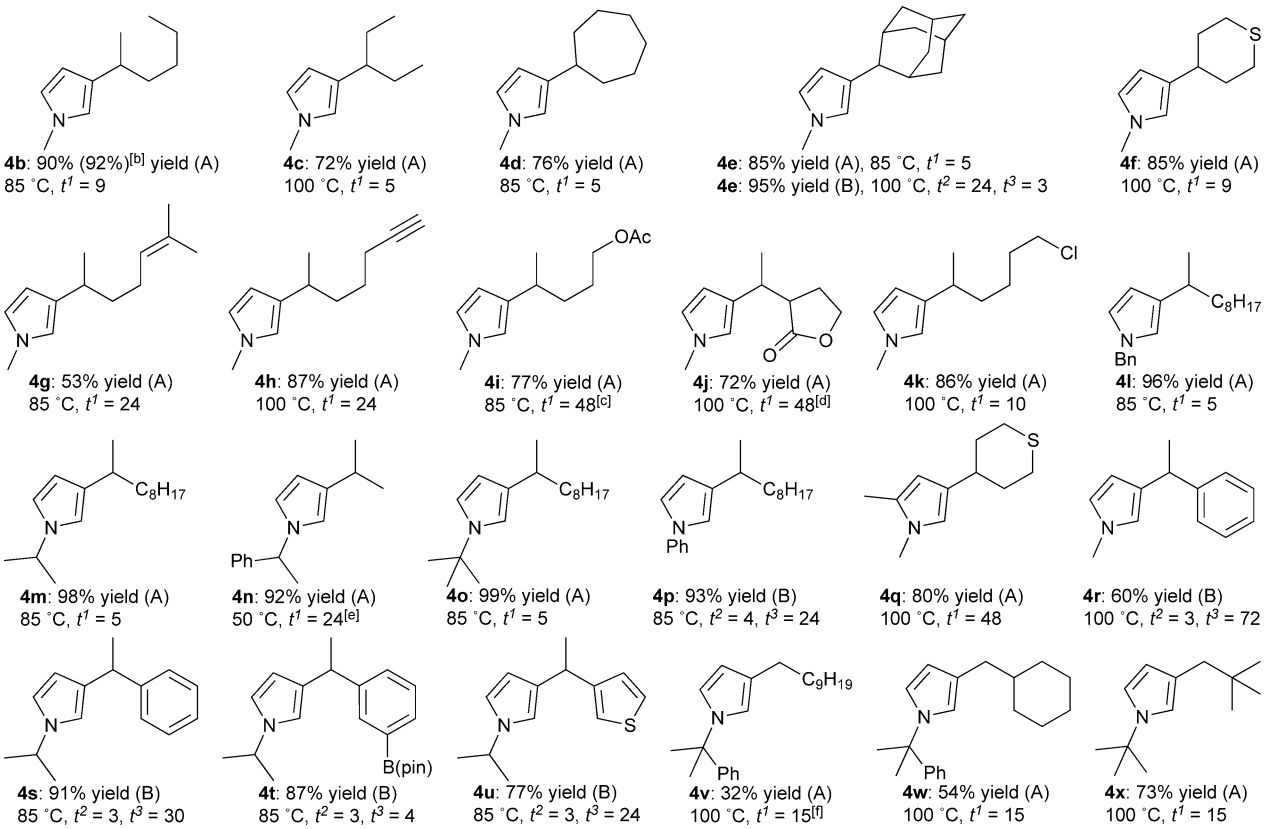
Scheme 2. Reductive β-2-decylation of **2a**: $HNTf_2$ versus $In(NTf_2)_3$. Yields of isolated **4a** based on **5a** are shown here.

As shown in Scheme 2, the performance of 3 mol% of $HNTf_2$ is comparable enough to that of 10 mol% of $In(NTf_2)_3$. $HNTf_2$ as a catalyst has several advantages over $In(NTf_2)_3$: 1) no indium as a rather rare metal is required, 2) no metallic waste remains after the reaction, 3) pre-synthesis of $In(NTf_2)_3$ from In_2O_3 and $HNTf_2$ is unnecessary, 4) $HNTf_2$ is commercially available and reasonable in price,[12] 5) the weight used of the catalyst can be reduced to less than one-tenth, that is, from 57.3 mg of $In(NTf_2)_3$ to 5.1 mg of $HNTf_2$ in the 0.6 mmol-scale reaction.

With the suitable reaction conditions in hand, we next explored the scope of the $HNTf_2$-catalyzed reaction (Table 2). Besides the 2-decyl group, the different length of the secondary alkyl chains and the cyclic structures were installed onto the β-position of **2a** exclusively (**4b**–**4f**). In the use of 2-adamantanone, its direct reduction occurred, giving 2-adamantanol (6% NMR yield). The undesired reduction was suppressed entirely by switching the procedure (method A) to method B, where **3a** is added after consumption of carbonyl compounds **5** (**4e**).[13] The compatibility of the functional groups, sulfide, alkenyl, alkynyl, ester, chloro, and boryl [B(pin) = B(pinacolate)], is noteworthy (**4f**–**4k**, **4q** and **4t**). The tolerance of the alkynyl part is especially remarkable and is thus an additional advantage of this method over the corresponding indium reaction because an indium catalyst is capable of activating the C≡C bond (**4h**).[14,15] In fact, use of $In(NTf_2)_3$ instead of $HNTf_2$ as a catalyst provided no **4h** due to the formation of a complex mixture of products. Pyrroles with a benzyl (Bn), iPr, 1-phenylethyl, *t*Bu, Ph, and cumyl group on the nitrogen atom also participated in this protocol (**4l**–**4p** and **4s**–**4x**). Of these, the reactions of *N*-iPr- and *N*-*t*Bu-pyrrole with **5a** allowed us to further reduce the loading of $HNTf_2$ to 1 mol% (**4m** and **4o**). Despite that 1,2-dimethylpyrrole has the two unsymmetrical β-sites, only the C4-position was alkylated (**4q**). In contrast to the pyrroles that have been used so far, no β-alkylation proceeded in the reaction using an electron-deficient pyrrole such as *N*-Boc-pyrrole (Boc = *tert*-butoxycarbonyl); reagents and conditions used are given in the reference section.[16] The reaction of pyrrole with no

Table 2. $HNTf_2$-catalyzed reductive β-alkylation of pyrroles.[a]

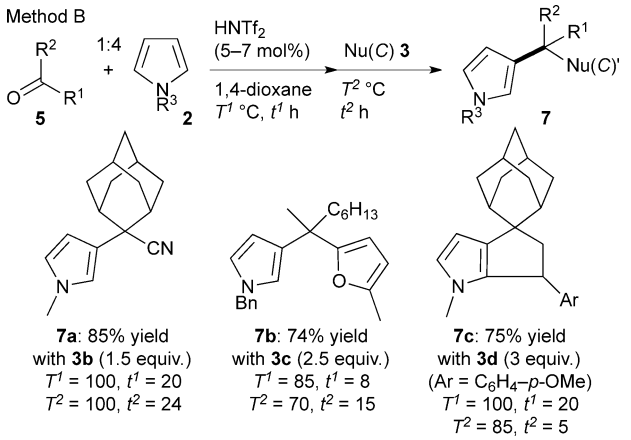




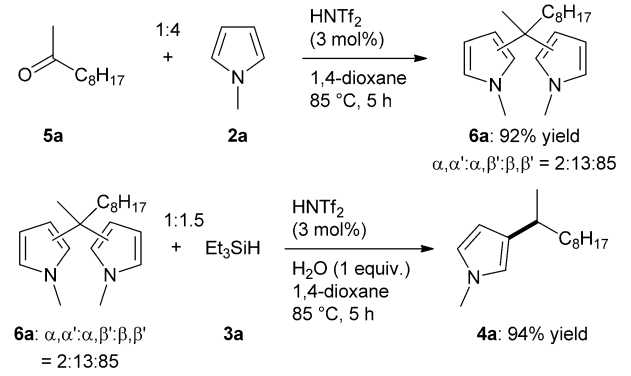
[a] Reagents: **5** (0.60 mmol), **2** (1.8 or 2.4 mmol), **3a** (0.90 or 1.8 mmol), $HNTf_2$ (6.0–42 μmol), 1,4-dioxane (0.60 mL). Yields of isolated **4** based on **5** are shown here. The methods used are shown in parentheses. See experimental section for further details.
[b] The yield when performed on 7.5 mmol scale is shown in parentheses.
[c] Ac = acetyl.
[d] The product was obtained as a 78:22 mixture of diastereomers.
[e] Performed on 7.0 mmol scale.
[f] **3a** (4.2 mmol) was used.

substituent on the nitrogen atom also led to a poor result; a reaction scheme is provided in the reference section.[17] These results suggest that electron-rich pyrroles with alkyl and aryl groups on the nitrogen atom should be essential for the progress of the reductive β-alkylation of pyrroles. When using aryl and heteroaryl ketones, method B is valid to exclude a small extent of α-alkylation that was concurrent with the β-alkylation in the use of method A (**4r**–**4u**). Upon introducing a primary alkyl group, the yield of the product was found to tend to increase with increasing the size of the alkyl unit (**4v**–**4x**). As Table 2 shows, 3–4 molar equivalents of **2** to **5** are used, but the excess amount of **2** can be recovered if desired. For example, 3 molar equivalents of *N*-(1-phenylethyl)pyrrole to acetone were used in the reaction giving **4n**. The pyrrole that remained unreacted was thus recovered with efficiency of 95%, which was calculated based on the excess amount of the pyrrole: 2 molar equivalents in this case (see the Experimental Section for further details). This result indicates that pyrrole substrates used as an excess amount are recoverable and reusable.

As a practical application, gram-scale synthesis can be performed. For example, **4b** and **4n** were prepared on 7.5 and 7.0 mmol scales, respectively, to provide 1.15 g of **4b** (92% yield) and 1.40 g of **4n** (92% yield).



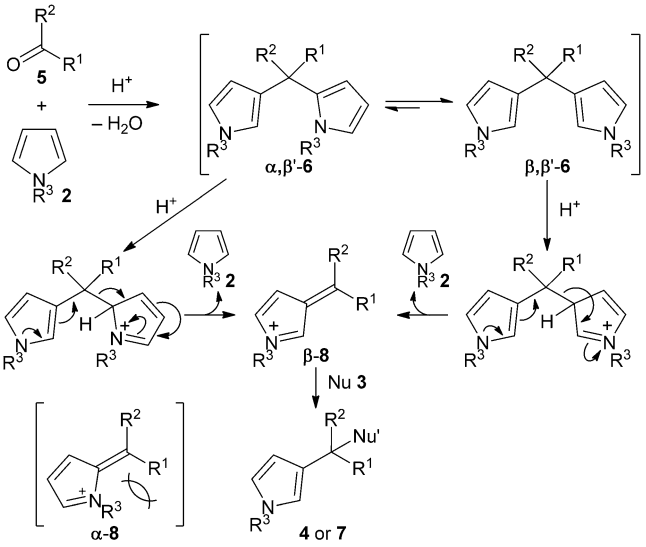
Scheme 3. $HNTf_2$-catalyzed β-alkylation of pyrroles with carbonyl compounds and carbon nucleophiles (**3b**: Me_3SiCN, **3c**: 2-methylfuran, **3d**: 4-vinylanisole).



Scheme 4. $HNTf_2$-catalyzed reaction for mechanistic studies.

Besides hydride nucleophile **3a**, carbon nucleophiles [Nu(*C*)] **3** such as Me_3SiCN (**3b**), 2-methylfuran (**3c**) and 4-vinylanisole (**3d**) can be used for extending a carbon–carbon bond (Scheme 3).[8] The use of such nucleophiles enables us to create the quaternary carbon center with the β-pyrrolyl group. Here again, the β-selectivities were perfectly controlled in all the cases. In the use of **3d**, the bicyclic ring was formed at once via a regioselective three carbon–carbon bond-forming cascade, where a benzylic cation generated after nucleophilic attack of the C=C bond of **3d** is likely to accept the α-carbon of the pyrrolyl group.

As thus far described, nitrogen-substituted β-alkylpyrroles with primary, secondary and tertiary alkyl groups can be prepared by utilizing the present method. Importantly, we have previously demonstrated that the benzyl and cumyl groups on the nitrogen atom are easily removable.[8] Therefore, combining this method and the deprotection reaction enables preparation of all six types including nitrogen-substituted and nitrogen-unsubstituted β-alkylpyrroles with primary, secondary and tertiary alkyl groups.



Scheme 5. A plausible reaction mechanism.

Some pieces of experimental observations are available for the mechanistic studies (Scheme 4). Thus, the reaction of **5a** with **2a** and $HNTf_2$ (3 mol%), but without Et_3SiH (**3a**), gave an isomeric mixture of dipyrrolylalkanes **6a**, as observed in the reaction performed by method B. The isolated mixture (**6a**) then reacted with **3a** in the presence of $HNTf_2$ (3 mol%) and H_2O,[18] giving **4a** exclusively in 94% yield. These results indicate that dipyrrolylalkanes **6** are intermediates in the three-component reaction. On the basis of these results and our previous ones,[7,8] a plausible mechanism is shown in Scheme 5, in which one pyrrole ring of **6** is fixed as the β-pyrrolyl ring, due actually to the non-formation of an α-alkylpyrrole derived inevitably from **α,α′-6**. The $HNTf_2$ (H^+) first assembles **5** and **2** into **6**, one pyrrole ring of which undergoes protonation and then eliminates to give cationic species **β-8** via the $C(sp^3)$–C(pyrrolyl) bond cleavage, as previously reported.[19] The trapping of **β-8** by nucleophile (Nu) **3** leads to product **4** or **7**. As previously noted, the origin of the observed β-selectivity would be ascribed to the dominant generation of **β-8** being much more stable than possible alternative cationic species **α-8** that has 1,3-allylic-type strain between R^1 and R^3.[20]

In conclusion, we have disclosed that $HNTf_2$ works as a powerful catalyst for the regioselective β-alkylation of pyrroles with carbonyl compounds and nucleophiles. The use of the Brønsted acid catalyst has several distinct advantages in comparison to the corresponding indium-catalyzed reaction. This method also features a wide range of substrate coverage with the high functional group tolerance, and thus would be useful and reliable tool for the synthesis of β-alkylpyrroles.

Experimental Section

General Remarks

All manipulations were conducted with a standard Schlenk technique under an argon atmosphere. Nuclear magnetic resonance (NMR) spectra were taken on a JEOL JMN-ECA 400 (^{1}H, 400 MHz; ^{13}C, 100 MHz) or JEOL JMN-ECA 500 (^{1}H, 500 MHz; ^{13}C, 125 MHz) spectrometer using tetramethylsilane (^{1}H and ^{13}C) as an internal standard. Analytical gas chromatography (GC) was performed on a Shimadzu model GC-2014 instrument equipped with a capillary column of InertCap 5 (5% phenyl polysilphenylene-siloxane, 30 m × 0.25 mm × 0.25 μm) using nitrogen as carrier gas. Gas chromatography–mass spectrometry (GC–MS) analyses were performed with a Shimadzu model GCMS-QP2010 instrument equipped with a capillary column of ID-BPX5 (5% phenyl polysilphenylene-siloxane, 30 m × 0.25 mm × 0.25 μm) by electron ionization at 70 eV using helium as carrier gas. Preparative recycling high-performance liquid chromatography (HPLC) was performed with JAI LC-9104 equipped with JAIGEL-GS320 column using a mixture of hexane–ethyl acetate (EtOAc) as eluent. Preparative recycling gel permeation chromatography (GPC) was performed with JAI LC-9105 equipped with JAIGEL-1H and JAIGEL-2H columns using chloroform as eluent. High-resolution mass spectra (HRMS) were obtained with a JEOL JMS-T100GCV spectrometer. All melting points were measured with a Yanaco Micro Melting Point apparatus and uncorrected. Kugelrohr bulb-to-bulb distillation was carried out with a Sibata glass tube oven GTO-250RS apparatus. Dibutyl ether and 1,4-dioxane were distilled under argon from sodium just prior to use. Toluene (PhMe) and chlorobenzene (PhCl) were distilled under argon from calcium chloride just prior to use. Propionitrile (EtCN) was distilled under argon from P_2O_5 just prior to use. Nitromethane was stored over molecular sieves 4 A (MS 4 A) under argon. Anhydrous *N*,*N*-dimethylformamide (DMF) was purchased from Wako pure chemical industries and used as received. *N*-(2-Phenylpropan-2-yl)pyrrole,[8] 6-heptyn-2-one,[21] and 1-[3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl]ethanone[8] were prepared according to the respective literature procedures. Unless otherwise noted, other substrates and reagents were commercially available and used as received.

Synthesis of *N*-Isopropylpyrrole

Based on the literature procedure,[22] *N*-isopropylpyrrole was synthesized with the following reagents: isopropylamine (5.91 g, 100 mmol), 2,5-dimethoxytetrahydrofuran (13.2 g, 100 mmol) and acetic acid (50.0 mL), and isolated in 29% yield (3.17 g) by vacuum distillation (85 °C/160 hPa). A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.45 (d, J = 5.4 Hz, 6H), 4.25 (sept, J = 5.4 Hz, 1H), 6.15 (t, J = 1.7 Hz, 2H), 6.73 (t, J = 1.7 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 24.0, 50.7, 107.7, 118.1. HRMS (FI) Calcd for $C_7H_{11}N$: M, 109.0892. Found: *m*/*z* 109.0868.

Synthesis of *N*-(1-Phenylethyl)pyrrole

Based on the literature procedure,[22] *N*-(1-phenylethyl)pyrrole was synthesized with the following reagents: 1-phenylethylamine (6.06 g, 50.0 mmol), 2,5-dimethoxytetrahydrofuran (6.61 g, 50.0 mmol) and acetic acid (22.5 mL), and isolated in 60% yield (5.15 g) by vacuum distillation (82 °C/133 Pa). A colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.83 (d, J = 6.9 Hz, 3H), 5.28 (q, J = 7.1 Hz, 1H), 6.19 (dd, J = 2.3, 1.7 Hz, 2H), 6.76 (dd, J = 2.3, 1.7 Hz, 2H), 7.09 (d, J = 7.5 Hz, 2H), 7.22–7.27 (m, 1H), 7.31 (t, J = 7.4 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.1, 58.1, 108.0, 119.5, 125.8, 127.4, 128.6, 143.5. HRMS (FI) Calcd for $C_{12}H_{13}N$: M, 171.1048. Found: *m*/*z* 171.1020.

Synthesis of *N*-*tert*-Butylpyrrole

N-*tert*-Butylpyrrole was synthesized according to the following modified literature procedure.[22] Under an argon atmosphere, a 300 mL two-necked round-bottomed flask was charged with *tert*-butylamine (29.3 g, 400 mmol), acetic acid (90.0 mL) and 2,5-dimethoxytetrahydrofuran (26.4 g, 200 mmol). After stirring at 80 °C for 50 h, the reaction mixture was diluted with Et_2O (200 mL). The resulting solution was washed with a 2 M NaOH aqueous solution (100 mL x 3), H_2O (100 mL) and brine (100 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by vacuum distillation (78 °C/80 hPa) provided *N*-*tert*-butylpyrrole (16.6 g, 67% yield) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.54 (s, 9H), 6.16 (t, J = 2.2 Hz, 2H), 6.84 (t, J = 2.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 30.8, 54.6, 107.4, 117.5. HRMS (FI) Calcd for $C_8H_{13}N$: M, 123.1048. Found: *m*/*z* 123.1017.

$HNTf_2$-Catalyzed Reductive β-Alkylation of Pyrroles with Carbonyl Compounds and Et_3SiH. A General Procedure of Method A for Table 2

A flame-dried 20 mL Schlenk tube was filled with argon and then charged with $HNTf_2$ [(1.69 mg, 6.00 μmol), (5.06 mg, 18.0 μmol), (8.43 mg, 30.0 μmol) or (11.8 mg, 42.0 μmol)] and 1,4-dioxane (0.60 mL). The solution was stirred at room temperature for 3 min. To this were added carbonyl compound **5** (0.600 mmol), pyrrole derivative **2** (1.80 or 2.40 mmol) and Et_3SiH (**3a**) (0.900, 1.80 or 4.20 mmol), and the resulting mixture was stirred at 50, 85 or 100 °C. After the time specified in Table 2 (see t^l), a saturated $NaHCO_3$ aqueous solution (0.3 mL) was added, and the aqueous phase was extracted with EtOAc (5 mL x 3). The combined organic layer was washed with brine (1 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane–EtOAc or hexane–$CHCl_3$ as eluent gave the corresponding product (**4**). The results are summarized in Table 2. Unless otherwise noted, products **4** synthesized here were fully characterized by ^{1}H and ^{13}C NMR spectroscopy and HRMS.

$HNTf_2$-Catalyzed Reductive β-Alkylation of Pyrroles with Carbonyl Compounds and Et_3SiH. A General Procedure of Method B for Table 2

A flame-dried 20 mL Schlenk tube was filled with argon and then charged with $HNTf_2$ [(5.06 mg, 18.0 μmol) or (11.8 mg, 42.0 μmol)] and 1,4-dioxane (0.60 mL). The solution was stirred at room temperature for 3 min. To this were added carbonyl compound **5** (0.600 mmol) and pyrrole derivative **2**

(1.80 or 2.40 mmol), and the resulting mixture was stirred at 85 or 100 °C for 3, 4 or 24 h. Et_3SiH (**3a**) (0.900 or 1.80 mmol) was then added, and the resulting solution was stirred further at 85 or 100 °C. After the time specified in Table 2 (see *t*[3]), the work-up process was carried out similarly as above. The results are summarized in Table 2. Unless otherwise noted, products **4** prepared here were fully characterized by ^1H and ^{13}C NMR spectroscopy and HRMS.

3-(Decan-2-yl)-1-methyl-1*H*-pyrrole (4a): The title compound was synthesized with the following reagents based on method A: **5a** (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 80:1). Compound **4a** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^1H NMR data are provided here. ^1H NMR (400 MHz, $CDCl_3$) δ 0.87 (t, J = 7.0 Hz, 3H), 1.17 (d, J = 6.9 Hz, 3H), 1.20–1.35 (m, 12H), 1.36–1.47 (m, 1H), 1.48–1.58 (m, 1H), 2.60 (sext, J = 7.0 Hz, 1H), 3.60 (s, 3H), 5.98 (t, J = 2.1 Hz, 1H), 6.37 (dd, J = 2.0, 1.8 Hz, 1H), 6.51 (t, J = 2.5 Hz, 1H).

3-(Hexan-2-yl)-1-methyl-1*H*-pyrrole (4b): The title compound was synthesized with the following reagents based on method A: for the reaction performed on 0.600 mmol scale: 2-hexanone (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 80:1); for the reaction performed on 7.50 mmol scale: 2-hexanone (7.50 mmol), **2a** (22.5 mmol), **3a** (11.3 mmol), $HNTf_2$ (225 μmol) and 1,4-dioxane (7.5 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 80:1). A colorless oil. ^1H NMR (500 MHz, $CDCl_3$) δ 0.88 (t, J = 7.0 Hz, 3H), 1.17 (d, J = 6.9 Hz, 3H), 1.22–1.34 (m, 4H), 1.37–1.48 (m, 1H), 1.49–1.59 (m, 1H), 2.60 (sext, J = 6.9 Hz, 1H), 3.60 (s, 3H), 5.99 (t, J = 2.2 Hz, 1H), 6.37 (t, J = 2.0 Hz, 1H), 6.50 (dd, J = 2.6, 2.3 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.1, 22.2, 22.9, 29.9, 31.8, 36.0, 38.5, 106.7, 118.0, 121.2, 131.1. HRMS (FI) Calcd for $C_{11}H_{19}N$: M, 165.1518. Found: *m*/*z* 165.1504.

1-Methyl-3-(pentan-3-yl)-1*H*-pyrrole (4c): The title compound was synthesized with the following reagents based on method A: 3-pentanone (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (30.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 100:1). A colorless oil. ^1H NMR (400 MHz, $CDCl_3$) δ 0.84 (t, J = 7.5 Hz, 6H), 1.40–1.51 (m, 2H), 1.51–1.65 (m, 2H), 2.25 (tt, J = 8.1, 5.6 Hz, 1H), 3.60 (s, 3H), 5.93 (t, J = 2.2 Hz, 1H), 6.35 (t, J = 1.9 Hz, 1H), 6.51 (t, J = 2.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.1, 29.0, 36.0, 41.2, 106.9, 119.0, 121.1, 128.6. HRMS (FI) Calcd for $C_{10}H_{17}N$: M, 151.1361. Found: *m*/*z* 151.1334.

3-Cycloheptyl-1-methyl-1*H*-pyrrole (4d): The title compound was synthesized with the following reagents based on method A: cycloheptanone (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 40:1). Compound **4d** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^1H NMR data are provided here. ^1H NMR (400 MHz, $CDCl_3$) δ 1.45–1.78 (m, 10H), 1.91–2.03 (m, 2H), 2.57–2.71 (m, 1H), 3.59 (s, 3H), 5.99 (dd, J = 2.3, 2.1 Hz, 1H), 6.37 (t, J = 1.9 Hz, 1H), 6.49 (dd, J = 2.5, 2.3 Hz, 1H).

3-(Adamant-2-yl)-1-methyl-1*H*-pyrrole (4e): The title compound was synthesized with the following reagents based on method A: 2-adamantanone (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL) or with the following reagents based on method B: 2-adamantanone (0.600 mmol), **2a** (2.40 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 30:1). Compound **4e** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^1H NMR data are provided here. ^1H NMR (500 MHz, $CDCl_3$) δ 1.51 (d, J = 13.2 Hz, 2H), 1.75 (s, 3H), 1.84–1.96 (m, 5H), 1.99 (d, J = 12.6 Hz, 2H), 2.15 (dd, J = 4.9, 3.2 Hz, 2H), 2.92 (s, 1H), 3.63 (s, 3H), 6.02 (t, J = 2.0 Hz, 1H), 6.42 (dd, J = 3.2, 2.0 Hz, 1H), 6.54 (t, J = 2.3 Hz, 1H).

1-Methyl-3-(tetrahydro-2*H*-thiopyran-4-yl)-1*H*-pyrrole (4f): The title compound was synthesized with the following reagents based on method A: tetrahydro-2*H*-thiopyran-4-one (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (30.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 20:1). Compound **4f** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^1H NMR data are provided here. ^1H NMR (400 MHz, $CDCl_3$) δ 1.73 (dtd, J = 13.3, 12.0, 3.4 Hz, 2H), 2.21 (dq, J = 13.8, 3.4 Hz, 2H), 2.47 (tt, J = 11.8, 3.3 Hz, 1H), 2.62–2.70 (m, 2H), 2.79 (td, J = 12.9, 2.5 Hz, 2H), 3.61 (s, 3H), 5.99 (t, J = 2.2 Hz, 1H), 6.38 (t, J = 1.8 Hz, 1H), 6.51 (t, J = 2.4 Hz, 1H).

1-Methyl-3-(6-methyl-5-hepten-2-yl)-1*H*-pyrrole (4g): The title compound was synthesized with the following reagents based on method A: 6-methyl-5-hepten-2-one (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by recycling GPC after column chromatography on silica gel (hexane/$CHCl_3$ = 5:1). Compound **4g** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^1H NMR data are provided here. ^1H NMR (400 MHz, $CDCl_3$) δ 1.19 (d, J = 6.9 Hz, 3H), 1.41–1.52 (m, 1H), 1.55–1.63 (m, 1H), 1.58 (s, 3H), 1.68 (d, J = 0.9 Hz, 3H), 1.97 (q, J = 7.6 Hz, 2H), 2.62 (sext, J = 7.0 Hz, 1H), 3.60 (s, 3H), 5.08–5.16 (m, 1H), 5.99 (t, J = 2.2 Hz, 1H), 6.37 (dd, J = 2.1, 1.8 Hz, 1H), 6.51 (t, J = 2.4 Hz, 1H).

3-(6-Heptyn-2-yl)-1-methyl-1*H*-pyrrole (4h): The title compound was synthesized with the following reagents based on method A: 6-heptyn-2-one (0.600 mmol), **2a** (1.80 mmol), **3a** (1.80 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 20:1). A colorless oil. ^1H NMR (500 MHz, $CDCl_3$) δ 1.20 (d, J = 6.9 Hz, 3H), 1.49–1.66 (m, 4H), 1.93 (t, J = 2.6 Hz, 1H), 2.17 (td, J = 6.7, 2.8 Hz, 2H), 2.63 (sext, J = 6.8 Hz, 1H), 3.60 (s, 3H), 5.98 (dd, J = 2.2, 1.9 Hz, 1H), 6.38 (t, J = 1.9 Hz, 1H), 6.51 (t, J = 2.4 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 18.6, 22.3, 26.6, 31.5, 36.0, 37.7, 68.0, 84.9, 106.6, 118.1, 121.4, 130.3. HRMS (FI) Calcd for $C_{12}H_{17}N$: M, 175.1361. Found: *m*/*z* 175.1350.

4-(1-Methyl-1*H*-pyrrol-3-yl)pentyl acetate (4i): The title compound was synthesized with the following reagents based on method A: 5-acetoxypentan-2-one (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 8:1). Compound **4i** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.20 (d, J = 7.1 Hz, 3H), 1.46–1.68 (m, 4H), 2.03 (s, 3H), 2.64 (sext, J = 6.9 Hz, 1H), 3.60 (s, 3H), 4.04 (t, J = 6.6 Hz, 2H), 5.98 (dd, J = 2.3, 2.1 Hz, 1H), 6.38 (dd, J = 2.1, 1.8 Hz, 1H), 6.51 (dd, J = 2.5, 2.3 Hz, 1H).

Dihydro-3-[1-(1-methyl-1*H*-pyrrol-3-yl)ethyl]-2(3*H*)-furanone (4j): The title compound was synthesized with the following reagents based on method A: 3-acetyldihydro-2(3*H*)-furanone (0.600 mmol), **2a** (1.80 mmol), **3** (1.80 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 3:1) as a 78/22 mixture of diastereomers. The mixture was then separated by recycling HPLC (hexane/EtOAc = 3:1). For the major isomer: A colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.27 (d, J = 7.2 Hz, 3H), 2.10–2.23 (m, 2H), 2.88 (td, J = 9.5, 3.8 Hz, 1H), 3.34 (qd, J = 7.1, 3.8 Hz, 1H), 3.61 (s, 3H), 4.10–4.20 (m, 2H), 6.01 (t, J = 2.3 Hz, 1H), 6.44 (t, J = 1.7 Hz, 1H), 6.53 (t, J = 2.4 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 16.5, 24.3, 31.7, 36.1, 45.8, 66.7, 107.1, 118.8, 121.8, 126.5, 178.8. HRMS (FI) Calcd for $C_{11}H_{15}NO_2$: M, 193.1103. Found: m/z 193.1085. For the minor isomer: A colorless oil. ^{1}H MNR (500 MHz, $CDCl_3$) δ 1.34 (d, J = 7.2 Hz, 3H), 2.05 (dq, J = 12.7, 8.5 Hz, 1H), 2.12–2.20 (m, 1H), 2.68 (td, J = 9.0, 4.5 Hz, 1H), 3.42 (qd, J = 7.2, 4.3 Hz, 1H), 3.59 (s, 3H), 3.93 (td, J = 8.7, 4.4 Hz, 1H), 4.09 (dt, J = 8.6, 8.0 Hz, 1H), 6.00 (t, J = 2.3 Hz, 1H), 6.43 (dd, J = 2.0, 1.7 Hz, 1H), 6.50 (t, J = 2.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 19.7, 23.8, 31.7, 36.1, 46.5, 66.8, 107.5, 119.8, 121.5, 124.1, 179.4. HRMS (FI) Calcd for $C_{11}H_{15}NO_2$: M, 193.1103. Found: m/z 193.1097.

3-(6-Chlorohexan-2-yl)-1-methyl-1*H*-pyrrole (4k): The title compound was synthesized with the following reagents based on method A: 6-chlorohexan-2-one (0.600 mmol), **2a** (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 20:1). Compound **4k** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 7. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.19 (d, J = 6.9 Hz, 3H), 1.36–1.61 (m, 4H), 1.76 (quint, J = 7.1 Hz, 2H), 2.62 (sext, J = 6.8 Hz, 1H), 3.51 (t, J = 6.9 Hz, 2H), 3.60 (s, 3H), 5.98 (dd, J = 2.3, 2.1 Hz, 1H), 6.37 (dd, J = 2.1, 1.8 Hz, 1H), 6.51 (dd, J = 2.5, 2.3 Hz, 1H).

1-Benzyl-3-(decan-2-yl)-1*H*-pyrrole (4l): The title compound was synthesized with the following reagents based on method A: **5a** (0.600 mmol), 1-benzyl-1*H*-pyrrole (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/$CHCl_3$ = 8:1). Compound **4l** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 7. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.87 (t, J = 7.0 Hz, 3H), 1.17 (d, J = 6.9 Hz, 3H), 1.21–1.34 (m, 12H), 1.37–1.48 (m, 1H), 1.49–1.57 (m, 1H), 2.61 (sext, J = 6.9 Hz, 1H), 5.00 (s, 2H), 6.03 (dd, J = 2.6, 1.7 Hz, 1H), 6.44 (dd, J = 2.0, 1.7 Hz, 1H), 6.59 (t, J = 2.5 Hz, 1H), 7.07–7.12 (m, 2H), 7.24–7.28 (m, 1H), 7.31 (tt, J = 7.3, 1.6 Hz, 2H).

3-(Decan-2-yl)-1-isopropyl-1*H*-pyrrole (4m): The title compound was synthesized with the following reagents based on method A: **5a** (0.600 mmol), *N*-isopropylpyrrole (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (6.00 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 50:1). A colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.87 (t, J = 6.9 Hz, 3H), 1.18 (d, J = 6.9 Hz, 3H), 1.20–1.35 (m, 12H), 1.37–1.47 (m, 1H), 1.43 (d, J = 6.6 Hz, 6H), 1.50–1.60 (m, 1H), 2.60 (sext, J = 6.9 Hz, 1H), 4.16 (sept, J = 6.7 Hz, 1H), 5.99 (t, J = 2.3 Hz, 1H), 6.48 (t, J = 2.0 Hz, 1H), 6.63 (dd, J = 2.6, 2.3 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.1, 21.9, 22.7, 23.9, 27.7, 29.4, 29.7, 29.9, 31.91, 31.94, 38.8, 50.4, 105.9, 114.5, 117.5, 130.3. HRMS (FI) Calcd for $C_{17}H_{31}N$: M, 249.2457. Found: m/z 249.2460.

3-Isopropyl-1-(1-phenylethyl)-1*H*-pyrrole (4n): The title compound was synthesized with the following reagents based on method A: acetone (7.00 mmol), *N*-(1-phenylethyl)pyrrole (21.0 mmol), **3a** (10.5 mmol), $HNTf_2$ (0.350 mmol), and 1,4-dioxane (7.0 mL), and isolated by column chromatography on silica gel (hexane/$CHCl_3$ = 3:1). In the process of purifying **4n**, *N*-(1-phenylethyl)pyrrole was also collected with a recovery efficiency of 95% (13.3 mmol), which was calculated based on 14.0 mmol of *N*-(1-phenylethyl)pyrrole used as an excess amount. A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.19 (d, J = 6.6 Hz, 3H), 1.20 (d, J = 6.9 Hz, 3H), 1.80 (d, J = 7.1 Hz, 3H), 2.81 (sept, J = 6.9 Hz, 1H), 5.20 (q, J = 7.1 Hz, 1H), 6.07 (t, J = 2.2 Hz, 1H), 6.49–6.54 (m, 1H), 6.66 (t, J = 2.5 Hz, 1H), 7.04–7.11 (m, 2H), 7.21–7.25 (m, 1H), 7.27–7.33 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.1, 24.05, 24.07, 26.5, 58.0, 106.5, 115.4, 119.0, 125.9, 127.3, 128.6, 131.7, 143.9. HRMS (FI) Calcd for $C_{15}H_{19}N$: M, 213.1518. Found: m/z 213.1530.

1-*tert*-Butyl-3-(decan-2-yl)-1*H*-pyrrole (4o): The title compound was synthesized with the following reagents based on method A: **5a** (0.600 mmol), *N*-*tert*-butylpyrrole (1.80 mmol), **3a** (0.900 mmol), $HNTf_2$ (6.00 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 40:1). Compound **4o** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.87 (t, J = 6.9 Hz, 3H), 1.18 (d, J = 7.2 Hz, 3H), 1.21–1.35 (m, 12H), 1.36–1.61 (m, 2H), 1.50 (s, 9H), 2.61 (sext, J = 6.9 Hz, 1H), 6.00 (dd, J = 2.6, 2.0 Hz, 1H), 6.58 (dd, J = 2.3, 1.7 Hz, 1H), 6.73 (t, J = 2.3 Hz, 1H).

3-(Decan-2-yl)-1-phenyl-1*H*-pyrrole (4p): The title compound was synthesized with the following reagents based on method B: **5a** (0.600 mmol), *N*-phenylpyrrole (2.40 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/$CHCl_3$ = 5:1). Compound **4p** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.87 (t, J = 6.9 Hz, 3H), 1.19–1.39 (m,

12H), 1.23 (d, $J=6.9$ Hz, 3H), 1.42–1.64 (m, 2H), 2.68 (sext, $J=6.9$ Hz, 1H), 6.21 (dd, $J=2.9$, 1.7 Hz, 1H), 6.86–6.89 (m, 1H), 7.02 (dd, $J=2.7$, 2.4 Hz, 1H), 7.19 (tt, $J=6.9$, 1.7 Hz, 1H), 7.35–7.42 (m, 4H).

1,2-Dimethyl-4-(tetrahydro-2*H*-thiopyran-4-yl)-1*H*-pyrrole (4q): The title compound was synthesized with the following reagents based on method A: tetrahydro-2*H*-thiopyran-4-one (0.600 mmol), 1,2-dimethylpyrrole (1.80 mmol), **3a** (1.80 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc=20:1). A white solid, mp=60–61 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.71 (dtd, $J=13.2$, 12.1, 3.4 Hz, 2H), 2.16–2.22 (m, 2H), 2.18 (d, $J=1.4$ Hz, 3H), 2.42 (tt, $J=11.6$, 3.3 Hz, 1H), 2.62–2.68 (m, 2H), 2.78 (ddd, 13.7, 12.2, 2.4 Hz, 2H), 3.46 (s, 3H), 5.75 (d, $J=0.9$ Hz, 1H), 6.31 (d, $J=2.0$ Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.9, 29.1, 33.4, 35.6, 36.0, 105.0, 116.7, 128.5, 128.7. HRMS (FI) Calcd for $C_{11}H_{17}NS$: M, 195.1082. Found: *m*/*z* 195.1082.

1-Methyl-3-(1-phenylethyl)-1*H*-pyrrole (4r): The title compound was synthesized with the following reagents based on method B: acetophenone (0.600 mmol), **2a** (1.80 mmol), **3a** (1.80 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by bulb-to-bulb distillation (100 °C/100 Pa) after column chromatography on silica gel (hexane/EtOAc=20:1). Compound **4r** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.56 (d, $J=7.3$ Hz, 3H), 3.58 (s, 3H), 4.00 (q, $J=7.2$ Hz, 1H), 5.96 (t, $J=2.1$ Hz, 1H), 6.29–6.33 (m, 1H), 6.51 (dd, $J=2.5$, 2.3 Hz, 1H), 7.14–7.20 (m, 1H), 7.24–7.31 (m, 4H).

1-Isopropyl-3-(1-phenylethyl)-1*H*-pyrrole (4s): The title compound was synthesized with the following reagents based on method B: acetophenone (0.600 mmol), *N*-isopropylpyrrole (2.40 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/$CHCl_3$=10:3). A colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.41 (d, $J=6.6$ Hz, 3H), 1.42 (d, $J=6.6$ Hz, 3H), 1.56 (d, $J=7.2$ Hz, 3H), 4.01 (q, $J=7.2$ Hz, 1H), 4.15 (sept, $J=6.7$ Hz, 1H), 5.95 (t, $J=2.3$ Hz, 1H), 6.41–6.45 (m, 1H), 6.63 (t, $J=2.6$ Hz, 1H), 7.14–7.19 (m, 1H), 7.24–7.30 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 22.8, 23.86, 23.91, 38.2, 50.5, 106.9, 115.5, 117.9, 125.6, 127.4, 128.1, 128.7, 148.1. HRMS (FI) Calcd for $C_{15}H_{19}N$: M, 213.1518. Found: *m*/*z* 213.1509.

1-Isopropyl-3-{1-[3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl]ethyl}-1*H*-pyrrole (4t): The title compound was synthesized with the following reagents based on method B: 1-[3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl]ethanone (0.600 mmol), *N*-isopropylpyrrole (2.40 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc/NEt_3=92:5:3). A viscous colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.34 (s, 12H), 1.40 (d, $J=6.6$ Hz, 3H), 1.41 (d, $J=6.6$ Hz, 3H), 1.56 (d, $J=7.2$ Hz, 3H), 4.03 (q, $J=7.2$ Hz, 1H), 4.14 (sept, $J=6.7$ Hz, 1H), 5.95 (dd, $J=2.3$, 2.0 Hz, 1H), 6.39–6.46 (m, 1H), 6.62 (t, $J=2.6$ Hz, 1H), 7.28 (t, $J=7.6$ Hz, 1H), 7.34 (ddd, $J=7.7$, 1.8, 1.4, Hz, 1H), 7.63 (ddd, $J=7.2$, 1.5, 1.2 Hz, 1H), 7.72–7.75 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 22.8, 23.86, 23.90, 24.9, 38.2, 50.5, 83.6, 107.0, 115.6, 117.8, 127.7, 128.8, 130.4, 132.3, 133.9, 147.3 (A signal of the boron-bound carbon atom was not detected due to quadrupolar relaxation of boron). HRMS (FD) Calcd for $C_{21}H_{30}BNO_2$: M, 339.2370. Found: *m*/*z* 339.2396.

1-Isopropyl-3-[1-(3-thienyl)ethyl]-1*H*-pyrrole (4u): The title compound was prepared with the following reagents based on method B: 3-acetylthiophene (0.600 mmol), *N*-isopropylpyrrole (2.40 mmol), **3a** (0.900 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc=20:1). A colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.411 (d, $J=6.6$ Hz, 3H), 1.413 (d, $J=6.6$ Hz, 3H), 1.56 (d, $J=7.0$ Hz, 3H), 4.09 (q, $J=7.1$ Hz, 1H), 4.15 (sept, $J=6.7$ Hz, 1H), 5.98 (t, $J=2.2$ Hz, 1H), 6.42–6.44 (m, 1H), 6.63 (t, $J=2.5$ Hz, 1H), 6.94–6.97 (m, 1H), 7.00 (dd, $J=4.9$, 1.3 Hz, 1H), 7.21 (dd, $J=5.0$, 3.0 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 22.8, 23.88, 23.90, 33.6, 50.5, 106.7, 115.3, 117.8, 119.3, 124.8, 127.8, 128.5, 148.9. HRMS (FI) Calcd for $C_{13}H_{17}NS$: M, 219.1082. Found: *m*/*z* 219.1088.

3-(Decan-1-yl)-1-(2-phenylpropan-2-yl)-1*H*-pyrrole (4v): The title compound was synthesized with the following reagents based on method A: 1-decanal (0.600 mmol), *N*-(2-phenylpropan-2-yl)pyrrole (2.40 mmol), **3a** (4.20 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc=5:1). Compound **4v** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.88 (t, $J=7.0$ Hz, 3H), 1.21–1.38 (m, 14H), 1.56 (quint, $J=7.5$ Hz, 2H), 1.86 (s, 6H), 2.45 (t, $J=7.8$ Hz, 2H), 6.04 (dd, $J=2.0$, 1.6 Hz, 1H), 6.52–6.55 (m, 1H), 6.70 (t, $J=2.6$ Hz, 1H), 6.95–6.99 (m, 2H), 7.21 (tt, $J=7.3$, 1.6 Hz, 1H), 7.24–7.30 (m, 2H).

3-(1-Cyclohexylmethyl)-1-(2-phenylpropan-2-yl)-1*H*-pyrrole (4w): The title compound was synthesized with the following reagents based on method A: cyclohexanecarboxaldehyde (0.600 mmol), *N*-(2-phenylpropan-2-yl)pyrrole (2.40 mmol), **3a** (1.80 mmol), $HNTf_2$ (42.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/$CHCl_3$=4:1). A colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.89 (qd, $J=12.0$, 2.9 Hz, 2H), 1.08–1.28 (m, 3H), 1.41 (ttt, $J=11.2$, 7.3, 3.7 Hz, 1H), 1.59–1.78 (m, 5H), 1.85 (s, 6H), 2.32 (d, $J=7.2$ Hz, 2H), 6.00 (dd, $J=2.8$, 1.9 Hz, 1H), 6.50 (dd, $J=2.5$, 1.9 Hz, 1H), 6.70 (t, $J=2.6$ Hz, 1H), 6.93–6.97 (m, 2H), 7.20 (tt, $J=7.3$, 1.6 Hz, 1H), 7.24–7.29 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.5, 26.7, 30.5, 33.4, 35.3, 39.5, 59.9, 108.4, 117.5, 118.7, 122.6, 124.9, 126.8, 128.3, 148.6. HRMS (FI) Calcd for $C_{20}H_{27}N$: M, 281.2144. Found: *m*/*z* 281.2158.

1-*tert*-Butyl-3-neopentyl-1*H*-pyrrole (4x): The title compound was synthesized with the following reagents based on method A: pivalaldehyde (0.600 mmol), *N*-*tert*-butylpyrrole (2.40 mmol), **3a** (0.900 mmol), $HNTf_2$ (18.0 μmol) and 1,4-dioxane (0.60 mL), and isolated by column chromatography on silica gel (hexane/EtOAc=100:1). Compound **4x** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in ref. 8. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.88 (s, 9H), 1.50 (s, 9H), 2.31 (s, 2H), 5.93 (dd, $J=2.6$, 2.0 Hz, 1H), 6.55 (dd, $J=2.3$, 2.0 Hz, 1H), 6.70 (t, $J=2.6$ Hz, 1H).

$HNTf_2$-Catalyzed β-Alkylation of Pyrroles with Carbonyl Compounds and Carbon Nucleophiles. A General Procedure for Scheme 3

A flame-dried 20 mL Schlenk tube was filled with argon and then charged with $HNTf_2$ [(4.22 mg, 15.0 μmol) or (5.90 mg, 21.0 μmol)] and 1,4-dioxane (0.30 or 2.4 mL). The solution was stirred at room temperature for 3 min. To this were added carbonyl compound **5** (0.300 mmol) and pyrrole derivative **2** (1.20 mmol), and the resulting mixture was stirred at 85 or 100 °C for 8 or 20 h. Carbon nucleophile **3** (0.450, 0.750 or 0.900 mmol) was then added, and the resulting solution was stirred further at 70, 85 or 100 °C. After the time specified in Scheme 3 (see t^2), a saturated $NaHCO_3$ aqueous solution (0.3 mL) was added, and the aqueous phase was extracted with EtOAc (5 mL x 3). The combined organic layer was washed with brine (1 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane–EtOAc or hexane–$CHCl_3$ as eluent gave the corresponding product (**7**). The results are summarized in Scheme 3. Unless otherwise noted, products **7** synthesized here were fully characterized by ^1H and ^{13}C NMR spectroscopy and HRMS.

2-(1-Methyl-1*H*-pyrrol-3-yl)-2-adamantanecarbonitrile (7a): The title compound was synthesized with the following reagents based on method B: 2-adamantanone (0.300 mmol), **2a** (1.20 mmol), **3b** (0.450 mmol), $HNTf_2$ (21.0 μmol) and 1,4-dioxane (0.30 mL), and isolated by column chromatography on silica gel (hexane/EtOAc = 3:1). A white solid, mp = 106–107 °C. ^1H NMR (500 MHz, $CDCl_3$) δ 1.61 (ddd, J = 13.1, 3.6, 2.7 Hz, 2H), 1.70–1.77 (m, 3H), 1.92 (ddd, J = 13.3, 3.6, 2.7 Hz, 2H), 1.97–2.05 (m, 3H), 2.41 (dd, J = 13.2, 2.3 Hz, 2H), 2.46 (t, J = 2.9 Hz, 2H), 3.64 (s, 3H), 6.10 (dd, J = 2.9, 1.7 Hz, 1H), 6.55 (dd, J = 2.3, 1.7 Hz, 1H), 6.57 (dd, J = 2.9, 2.3 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.9, 31.5, 34.1, 34.9, 36.4, 37.63, 37.64, 42.9, 106.5, 119.6, 122.1, 123.0, 124.9. HRMS (FD) Calcd for $C_{16}H_{20}N_2$: M, 240.1627. Found: m/z 240.1624.

2-(1-Benzyl-1*H*-pyrrol-3-yl)-2-(5-methylfuran-2-yl)octane (7b): The title compound was synthesized with the following reagents based on method B: 2-octanone (0.300 mmol), 1-benzyl-1*H*-pyrrole (1.20 mmol), **3c** (0.750 mmol), $HNTf_2$ (15.0 μmol) and 1,4-dioxane (2.4 mL), and isolated by column chromatography on silica gel (hexane/$CHCl_3$ = 4:1). Compound **7b** has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported in the literature.[23] Therefore, only ^1H NMR data are provided here. ^1H NMR (400 MHz, $CDCl_3$) δ 0.85 (t, J = 6.9 Hz, 3H), 1.07–1.31 (m, 8H), 1.51 (s, 3H), 1.75–1.86 (m, 1H), 1.88–2.00 (m, 1H), 2.24 (d, J = 0.9 Hz, 3H), 5.00 (s, 2H), 5.80–5.83 (m, 1H), 5.85 (d, J = 3.2 Hz, 1H), 6.06 (dd, J = 2.7, 1.8 Hz, 1H), 6.45 (dd, J = 2.3, 1.8 Hz, 1H), 6.56 (dd, J = 2.7, 2.3 Hz, 1H), 7.04–7.10 (m, 2H), 7.22–7.34 (m, 3H).

5′,6′-Dihydro-6′-(4-methoxyphenyl)-1′-methyl-spiro[adamantane-2,4′(1′*H*)-cyclopenta[*b*]pyrrole] (7c): The title compound was synthesized with the following reagents based on method B: 2-adamantanone (0.300 mmol), **2a** (1.20 mmol), **3d** (0.900 mmol), $HNTf_2$ (21.0 μmol) and 1,4-dioxane (0.30 mL), and isolated by column chromatography on silica gel (hexane/$CHCl_3$ = 2:1). A viscous colorless oil. ^1H NMR (500 MHz, $CDCl_3$) δ 1.56–1.72 (m, 6H), 1.76 (s, 2H), 1.78–1.85 (m, 2H), 1.95 (quint, J = 2.9 Hz, 1H), 2.02 (ddd, J = 12.7, 5.4, 3.3 Hz, 1H), 2.11 (dd, J = 13.2, 6.6 Hz, 1H), 2.33 (ddd, J = 12.6, 6.3, 3.5 Hz, 1H), 2.46 (ddd, J = 13.3, 6.0, 3.5 Hz, 1H), 3.03 (dd, J = 13.2, 8.3 Hz, 1H), 3.16 (s, 3H), 3.79 (s, 3H), 4.17 (dd, J = 8.0, 6.9 Hz, 1H), 6.21 (d, J = 2.9 Hz, 1H), 6.50 (d, J = 2.6 Hz, 1H), 6.83 (dt, J = 8.9, 2.6 Hz, 2H), 7.07 (dt, J = 8.6, 2.4 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.4, 27.6, 33.9, 34.3, 34.4, 34.8, 35.1, 37.4, 38.9, 39.8, 42.2, 49.8, 54.3, 55.2, 106.0, 113.9, 123.2, 128.4, 134.8, 137.7, 137.9, 158.0. HRMS (FD) Calcd for $C_{24}H_{29}NO$: M, 347.2249. Found: m/z 347.2469.

$HNTf_2$-Catalyzed Synthesis of Dipyrrolyldecanes 6a by Treatment of 2-Decanone (5a) and *N*-Methylpyrrole (2a) (Scheme 4)

A flame-dried 50 mL Schlenk tube was filled with argon and then charged with $HNTf_2$ (59.0 mg, 210 μmol) and 1,4-dioxane (7.0 mL). The solution was stirred at room temperature for 3 min. To this were added **5a** (1.09 g, 7.00 mmol) and **2a** (2.27 g, 28.0 mmol) successively, and the resulting mixture was stirred at 85 °C for 5 h. A saturated $NaHCO_3$ aqueous solution (2 mL) was added, and the aqueous phase was extracted with EtOAc (50 mL x 3). The combined organic layer was washed with brine (20 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 20:1) gave dipyrrolyldecanes **6a** (1.92 g, 92% yield) as a mixture of three isomers including **α,α′-6a**, **α,β′-6a** and **β,β′-6a**. The result is summarized in Scheme 4. ^1H NMR spectra showed that **β,β′-6a** is a major isomer, along with **α,β′-6a** and a small amount of **α,α′-6a**. The ratio of **α,α′-6a**:**α,β′-6a**:**β,β′-6a** was determined to be 2:13:85 by GC analysis. The two major isomers, **α,β′-6a** and **β,β′-6a**, have already appeared in the literature, and their spectral and analytical data are in good agreement with those reported in ref. 7. Due to the small amount of **α,α′-6a** produced here, other reaction for synthesizing **α,α′-6a** was carried out under the reaction conditions shown in the next section, and **α,α′-6a** was obtained as a pure form.

$HNTf_2$-Catalyzed Synthesis of 2,2-Bis(1-methyl-1*H*-pyrrol-2-yl)decane (α,α′-6a) by Treatment of 2-Decanone (5a) and *N*-Methylpyrrole (2a)

A flame-dried 20 mL Schlenk tube was filled with argon and then charged with $HNTf_2$ (5.06 mg, 18.0 μmol) and 1,4-dioxane (0.60 mL). The solution was stirred at room temperature for 3 min. To this were added **5a** (93.8 mg, 0.600 mmol) and **2a** (195 mg, 2.40 mmol) successively, and the resulting mixture was stirred at room temperature for 3 h. A saturated $NaHCO_3$ aqueous solution (0.3 mL) was added, and the aqueous phase was extracted with EtOAc (5 mL x 3). The combined organic layer was washed with brine (1 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/$CHCl_3$ = 6:1) gave **α,α′-6a** (29.0 mg, 16% yield) as a viscous colorless oil. ^1H NMR (500 MHz, $CDCl_3$) δ 0.87 (t, J = 7.0 Hz, 3H), 1.04–1.34 (m, 12H), 1.59 (s, 3H), 2.01–2.09 (m, 2H), 3.02 (s, 6H), 6.02 (dd, J = 3.6, 2.7 Hz, 2H), 6.07 (dd, J = 3.8, 2.0 Hz, 2H), 6.45

(t, $J=2.3$ Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.1, 22.7, 24.0, 26.7, 29.4, 29.6, 30.2, 31.9, 34.3, 38.7, 39.7, 105.8, 106.7, 122.8, 137.7. HRMS (FI) Calcd for $C_{20}H_{32}N_2$: M, 300.2566. Found: *m*/*z* 300.2568.

$HNTf_2$-Catalyzed Synthesis of 3-(Decan-2-yl)-1-methyl-1*H*-pyrrole (4a) by Treatment of Dipyrrolyldecanes 6a, Et_3SiH (3a) and H_2O (Scheme 4)

A flame-dried 20 mL Schlenk tube was filled with argon and then charged with $HNTf_2$ (2.53 mg, 9.00 μmol) and 1,4-dioxane (0.30 mL). The solution was stirred at room temperature for 3 min. To this were added **6a** (90.1 mg, 0.300 mmol), **3a** (52.3 mg, 0.450 mmol) and H_2O (5.40 mg, 0.300 mmol) successively, and the resulting mixture was stirred at 85 °C for 5 h. A saturated $NaHCO_3$ aqueous solution (0.3 mL) was added, and the aqueous phase was extracted with EtOAc (5 mL x 3). The combined organic layer was washed with brine (1 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 40:1) gave **4a** (62.6 mg, 94% yield). The result is summarized in Scheme 4. The full data on ^{1}H NMR, ^{13}C NMR spectroscopy and HRMS analysis of **4a** have been already collected in ref. 8.

Acknowledgements

Partial financial support from Nissan Chemical Industries, L.T.D. is gratefully acknowledged.

References

[1] For selected recent reviews, see: a) N. K. Garg, B. M. Stoltz, *Chem. Commun.* **2006**, 3769; b) N. R. Williamson, P. C. Fineran, F. J. Leeper, G. P. C. Salmond, *Nat. Rev. Microbiol.* **2006**, *4*, 887; c) C.-C. Chang, W.-C. Chen, T.-F. Ho, H.-S. Wu, Y.-H. Wei, *J. Biosci. Bioeng.* **2011**, *111*, 501. For selected recent reports, see: d) U. Robben, I. Lindner, W. Gärtner, *J. Am. Chem. Soc.* **2008**, *130*, 11303; e) C. P. Soldermann, R. Vallinayagam, M. Tzouros, R. Neier, *J. Org. Chem.* **2008**, *73*, 764; f) J. H. Frederich, P. G. Harran, *J. Am. Chem. Soc.* **2013**, *135*, 3788; g) C. Vergeiner, S. Banala, B. Kräutler, *Chem. Eur. J.* **2013**, *19*, 12294.

[2] For selected recent examples, see: a) L. Jiao, E. Hao, M. G. H. Vicente, K. M. Smith, *J. Org. Chem.* **2007**, *72*, 8119; b) G. Zotti, B. Vercelli, A. Berlin, *Chem. Mater.* **2008**, *20*, 397; c) X. Lv, L.-J. Hong, Y. Li, M.-J. Yang, *J. Appl. Polym. Sci.* **2009**, *112*, 1287; d) M. Krayer, M. Ptaszek, H.-J. Kim, K. R. Meneely, D. Fan, K. Secor, J. S. Lindsey, *J. Org. Chem.* **2010**, *75*, 1016; e) J. T. Lee, D.-H. Chae, Z. Ou, K. M. Kadish, Z. Yao, J. L. Sessler, *J. Am. Chem. Soc.* **2011**, *133*, 19547; f) T.-T. Bui, A. Iordache, Z. Chen, V. V. Roznyatovskiy, E. Saint-Aman, J. M. Lim, B. S. Lee, S. Ghosh, J.-C. Moutet, J. L. Sessler, D. Kim, C. Bucher, *Chem. Eur. J.* **2012**, *18*, 5853.

[3] *Heterocyclic Chemistry*, 5th ed. (Eds.: J. A. Joule, K. Mills) Wiley, New York, **2010**, pp. 9–10.

[4] For a selected review on the Friedel–Crafts alkylation of pyrroles, see: B. A. Trofimov, N. A. Nedolya In *Comprehensive Heterocyclic Chemistry III*, *Vol.* 3 (Eds.: A. R. Katritzky, C. A. Ramsden, E. F. V. Scriven, R. J. K. Taylor, G. Jones), Elsevier, Oxford, **2008**, pp. 110–134.

[5] For reviews on β-alkylation of pyrroles, see: a) H. J. Anderson, C. E. Loader, *Synthesis* **1985**, 353; b) W. D. Harman, *Chem. Rev.* **1997**, *97*, 1953; c) B. C. Brooks, T. B. Gunnoe, W. D. Harman, *Coord. Chem. Rev.* **2000**, *206–207*, 3; d) T. Tsuchimoto, *Chem. Eur. J.* **2011**, *17*, 4064. For selected recent reports on β-alkylation of pyrroles, see: e) D. Prajapati, M. Gohain, B. J. Gogoi, *Tetrahedron Lett.* **2006**, *47*, 3535; f) O. I. Shmatova, N. E. Shevchenko, E. S. Balenkova, G.-V. Röschenthaler, V. G. Nenajdenko, *Eur. J. Org. Chem.* **2013**, 3049; see also refs. 6–8.

[6] Among the strategies for the S_EAr-based β-alkylation of pyrroles, a bulky triisopropylsilyl group on the nitrogen atom has been known to direct incoming electrophiles to the β-position due to its effective steric shielding of the α-position. For selected recent reports on the β-alkylation of *N*-$(iPr)_3Si$-pyrrole, see: a) C. Berini, F. Minassian, N. Pelloux-Léon, J.-N. Denis, Y. Vallée, C. Philouze, *Org. Biomol. Chem.* **2008**, *6*, 2574; b) J. Barluenga, A. Fernández, F. Rodríguez, F. J. Fañanás, *Chem. Eur. J.* **2009**, *15*, 8121; c) C. Berini, N. Pelloux-Léon, F. Minassian, J.-N. Denis, *Org. Biomol. Chem.* **2009**, *7*, 4512; d) F. Martinelli, A. Palmieri, M. Petrini, *Chem. Eur. J.* **2011**, *17*, 7183; e) L. Boiaryna, M. K. El Mkaddem, C. Taillier, V. Dalla, M. Othman, *Chem. Eur. J.* **2012**, *18*, 14192; f) F. de Nanteuil, J. Loup, J. Waser, *Org. Lett.* **2013**, *15*, 3738; g) S. Lancianesi, A. Palmieri, M. Petrini, *Adv. Synth. Catal.* **2013**, *355*, 3285.

[7] T. Tsuchimoto, T. Wagatsuma, K. Aoki, J. Shimotori, *Org. Lett.* **2009**, *11*, 2129.

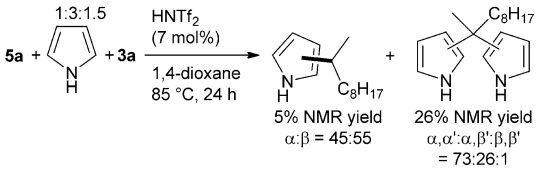
[8] T. Tsuchimoto, M. Igarashi, K. Aoki, *Chem. Eur. J.* **2010**, *16*, 8975. Due to a request from one reviewer, results of some experiments performed to confirm whether $HNTf_2$ is a true catalyst or not in the preceding study are collected in the Supporting Information.

[9] For a report on increases in consumption and price of indium during the last few decades, see: T. G. Goonan, "*Materials Flow of Indium in the United States in 2008 and 2009*" that can be found at http://pubs.usgs.gov/circ/1377.

[10] For synthesis of $In(NTf_2)_3$ ($Tf = SO_2CF_3$), see: a) C. G. Frost, J. P. Hartley, D. Griffin, *Tetrahedron Lett.* **2002**, *43*, 4789; b) M. Nakamura, K. Endo, E. Nakamura, *Adv. Synth. Catal.* **2005**, *347*, 1681. For synthesis of $In(ONf)_3$ ($Nf = SO_2C_4F_9$), see: c) T. Tsuchimoto, H. Matsubayashi, M. Kaneko, E. Shirakawa, Y. Kawakami, *Angew. Chem.* **2005**, *117*, 1360; *Angew. Chem. Int. Ed.* **2005**, *44*, 1336.

[11] $In(NTf_2)_3$ is currently commercially available from Sigma–Aldrich, but is expensive; 20,700 yen/1 g.

[12] $HNTf_2$ is commercially available at 20,000 yen/250 g (= 80 yen/1 g) from Kanto Chemical Co., Inc.

[13] Disappearance of carbonyl compounds **5** followed by formation of dipyrrolylalkanes **6** can be confirmed by GC and GC–MS analysis.
[14] For our representative reports on indium-catalyzed transformation via activation of C≡C bonds, see: a) T. Tsuchimoto, T. Maeda, E. Shirakawa, Y. Kawakami, *Chem. Commun.* **2000**, 1573; b) T. Tsuchimoto, K. Hatanaka, E. Shirakawa, Y. Kawakami, *Chem. Commun.* **2003**, 2454; c) T. Tsuchimoto, H. Matsubayashi, M. Kaneko, Y. Nagase, T. Miyamura, E. Shirakawa, *J. Am. Chem. Soc.* **2008**, *130*, 15823; d) T. Tsuchimoto, M. Kanbara, *Org. Lett.* **2011**, *13*, 912; e) Y. Nagase, H. Shirai, M. Kaneko, E. Shirakawa, T. Tsuchimoto, *Org. Biomol. Chem.* **2013**, *11*, 1456. See also refs. 7, 10c.
[15] Other research groups have also reported indium-catalyzed transformation by way of activation of C≡C bonds. See an important review: Z.-L. Shen, S.-Y. Wang, Y.-K. Chok, T.-P. Loh, *Chem. Rev.* **2013**, *113*, 271.
[16] **5a** (0.60 mmol), *N*-Boc-pyrrole (1.8 mmol), **3a** (0.90 mmol), $HNTf_2$ (18 μmol), 1,4-dioxane (0.60 mL), 85 °C, 5 h.
[17] 

[18] The process of the $HNTf_2$-catalyzed reaction of **5a** with **2a** produces one molar equivalent of H_2O along with the formation of **6a**. Accordingly, the reaction was performed in the presence of H_2O (1 equiv.).
[19] a) D. M. Wallace, S. H. Leung, M. O. Senge, K. M. Smith, *J. Org. Chem.* **1993**, *58*, 7245; b) G. R. Geier III, B. J. Littler, J. S. Lindsey, *J. Chem. Soc. Perkin Trans. 2* **2001**, 701; c) A. Auger, A. J. Muller, J. C. Swarts, *Dalton Trans.* **2007**, 3623.
[20] a) W. Adam, J. Gläser, K. Peters, M. Prein, *J. Am. Chem. Soc.* **1995**, *117*, 9190; b) Y. Yokoyama, *Chem. Eur. J.* **2004**, *10*, 4388.
[21] For synthesis of 6-heptyn-2-one, see: a) P. E. Peterson, R. J. Kamat, *J. Am. Chem. Soc.* **1969**, *91*, 4521; for spectral and analytical data of 6-heptyn-2-one, see: b) C. Le Drian, A. E. Greene, *J. Am. Chem. Soc.* **1982**, *104*, 5473; c) B. M. Trost, M. J. Bartlett, *Org. Lett.* **2012**, *14*, 1322.
[22] A. D. Josey, *Org. Synth.* **1967**, *47*, 81.
[23] T. Tsuchimoto, T. Ainoya, K. Aoki, T. Wagatsuma, E. Shirakawa, *Eur. J. Org. Chem.* **2009**, 2437.

