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Investigation of the Scope of a New Route to ABCD-Bilanes and ABCD-Porphyrins

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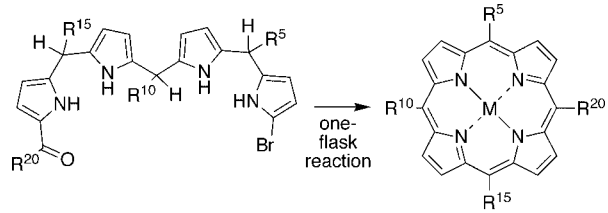
Received May 14, 2008



A new route to bilanes and porphyrins bearing four distinct *meso* substituents has been studied to elucidate the scope and gain entry to previously inaccessible compounds. The route entails (i) synthesis of a 1-bromo-19-acylbilane by acid-catalyzed condensation of a 1-acyldipyrromethane and a 9-bromodipyrromethane-1-carbinol and (ii) intramolecular cyclization of the 1-bromo-19-acylbilane in the presence of a metal salt ($MgBr_2$, 3 mol equiv) and a non-nucleophilic base (DBU, 10 mol equiv) in a noncoordinating solvent (toluene) at 115 °C exposed to air to afford the corresponding magnesium(II) porphyrin. In this study, two sets of bilanes were initially prepared to explore substituent effects. In the first set, all bilanes vary only in the nature of the substituent at the 10-position. In the second set, all bilanes vary only in the nature of the substituent attached to the acyl unit (the 20-position). The substituents examined at the 10- and 20-positions include alkyl, aryl (electron-rich, electron-deficient, hindered), heteroaryl, ester, or no substituent (−H). The bilanes were obtained in 35−87% yield, and the target porphyrins in up to 60% yield. Further study of the scope focused on bilanes and porphyrins bearing three heterocyclic substituents (*o*-, *m*-, *p*-pyridyl) or four alkyl groups (ethyl, propyl, butyl, pentyl), in which case microwave irradiation was used for the porphyrin-forming step. Altogether, 17 bilanes and 19 porphyrins were prepared and characterized. In summary, the new route provides access to *meso*-substituted bilanes and porphyrins for which access is limited via other methods.

Introduction

Porphyrins bearing multiple substituents in distinct patterns are valuable constituents in biomimetic and materials chemistry. One route to porphyrins bearing four different *meso* substituents (i.e., ABCD-porphyrins) relies on the condensation of an ABC-dipyrromethane-1,9-dicarbinol and a D-dipyrromethane followed by oxidation of the resulting porphyrinogen.[1–3] The reaction is compatible with a variety of substituents, and proceeds without detectable scrambling in many cases. (Scrambling refers to the cleavage of pyrromethane moieties and recombination of fragments thereof to form undesired macrocycles containing distinct patterns or combinations of substituents.[4–8]) The chief limitations of this "2 + 2" method reside in the macrocycle-forming step: the reaction is carried out in dilute solution (2.5−25 mM reactants), the yield is low (20−30%), dichloromethane is typically used as the solvent, and an added chemical oxidant (DDQ) is employed for conversion of the porphyrinogen to the porphyrin. In addition, certain types of substituents afford poor results (e.g., alkyl,[2] heterocyclic,[2] no

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(3) Zaidi, S. H. H.; Fico, R. M., Jr.; Lindsey, J. S. *Org. Process Res. Dev.* **2006**, *10*, 118–134.
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10.1021/jo8010396 CCC: $40.75 © 2008 American Chemical Society
Published on Web 08/07/2008

substituent[9,10]). An alternative route relies on treatment of an intact porphyrin with nucleophiles (e.g., organolithiums) followed by oxidation to form the porphyrin bearing distinct patterns of substituents.[11]

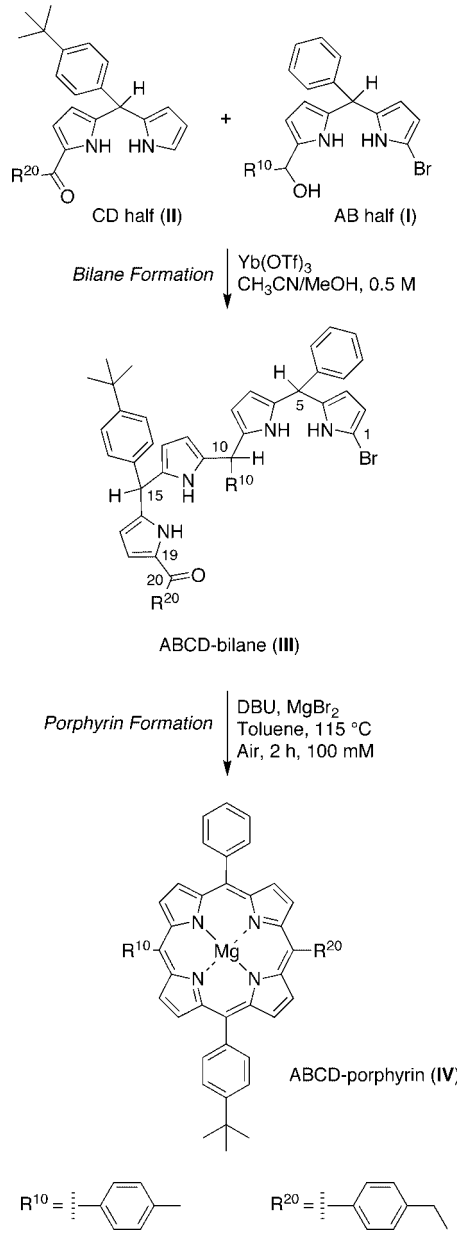
We recently developed a new strategy for the synthesis of ABCD-porphyrins that relies on two key reactions: (1) acid-catalyzed condensation of an AB-substituted 1-bromo-dipyrromethane-9-carbinol (**I**) and a CD-substituted 1-acyldipyrromethane (**II**) to give the corresponding 19-acyl-1-bromobilane (**III**), and (2) cyclization of the bilane (**III**) in the presence of a non-nucleophilic base (DBU), a noncoordinating solvent (toluene), and a metal reagent ($MgBr_2$) at 115 °C exposed to air. In the one case examined, cyclization to give the ABCD-porphyrin **IV** proceeded in 65% yield (Scheme 1).[12]

The "porphyrins via bilanes" strategy has several attractive features: (i) no detectable scrambling at any stage of the synthesis, (ii) good yield (up to 60%) at high concentration (100 mM) for the macrocycle-forming step, (iii) synthesis of the porphyrin in a relatively short period of time (e.g., <1 week), (iv) no added chemical oxidant for porphyrin formation, (v) magnesium porphyrins as the products, which easily undergo demetalation, and (vi) facile chromatographic purification. Our chief focus in developing this approach has been to broaden access to porphyrins, yet the accompanying entrée to *meso*-substituted bilanes may be of comparable value.

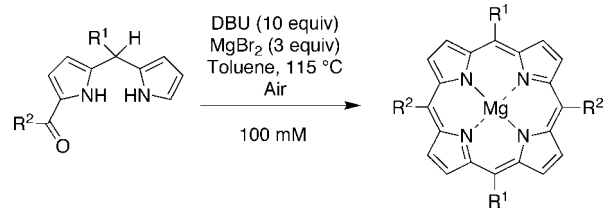
The reaction conditions for the intramolecular cyclization of a 19-acyl-1-bromobilane also have been applied to the condensation of two 1-acyldipyrromethane molecules to give the corresponding *trans*-A_2B_2-porphyrin without formation of an isolable bilane (Scheme 2). Upon examination of a wide variety of 1-acyldipyrromethanes,[13] the reaction conditions were found to be particularly well-suited to the synthesis of porphyrins that bear less than four *meso* substituents (e.g., *trans*-A_2-porphyrins). The limiting example of such sparsely substituted porphyrins entails the condensation of two 1-formyldipyrromethane molecules to give porphine (all *meso*-substituents = H).[14] The reaction conditions also were well-suited to the presence of pyridyl groups, which enabled the synthesis of a variety of novel porphyrins bearing pyridyl groups via rational (e.g., *trans*-A_2B_2-, *trans*-A_2-porphyrin) or statistical (e.g., *cis*-A_2-, *cis*-AB-, A-porphyrin) approaches. Greater structural diversity was not achievable owing to the use of 1-acyldipyrromethanes (i.e., ABCD-porphyrins were not accessible), however, and the reaction conditions were poorly compatible with alkyl substituents (e.g., *trans*-A_2B_2-porphyrins bearing four alkyl groups could not be prepared).

The prior study of the new methodology for the intramolecular cyclization of a 19-acyl-1-bromobilane did not examine the scope of application.[12] In the study described herein, we investigated the scope of substituents that can be introduced to ABCD-bilanes and the corresponding ABCD-porphyrins. The groups of interest include alkyl chains, aryl units with electron-withdrawing or electron-releasing groups, bulky substituents,

SCHEME 1



SCHEME 2



heterocycles, and no substituent (−H). Elucidating the type of substituents that could be tolerated at the 10- and 20-positions (R^{10}, R^{20}) was of most immediate interest because such sites engage in reaction to form the bilane and porphyrin, respectively. The R^{10} substituent derives from the 1-bromodipyrromethane-9-carbinol (**I**); this substituent must tolerate acylation of the dipyrromethane, reduction to the α-carbinol, and acid-catalyzed condensation to give the bilane. The R^{20} substituent is not involved in bilane formation but resides at the α-position where carbon−carbon bond formation must occur in the cyclization

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(10) Taniguchi, M.; Balakumar, A.; Fan, D.; McDowell, B. E.; Lindsey, J. S. *J. Porphyrins Phthalocyanines* **2005**, *9*, 554–574.
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(12) Dogutan, D. K.; Zaidi, S. H. H.; Thamyongkit, P.; Lindsey, J. S. *J. Org. Chem.* **2007**, *72*, 7701–7714.
(13) Dogutan, D. K.; Ptaszek, M.; Lindsey, J. S. *J. Org. Chem.* **2008**, *73*, 6187–6201.
(14) Dogutan, D. K.; Ptaszek, M.; Lindsey, J. S. *J. Org. Chem.* **2007**, *72*, 5008–5011.

to give the porphyrin (**IV**) under magnesium-mediated, oxidative conditions. The substituents at positions 5 and 15 (R^5, R^{15}) are also of interest; however, studies of numerous porphyrin-forming reactions indicate that there is greater latitude for diverse substituents at the center of dipyrromethane moieties than at the reacting α-positions.[2]

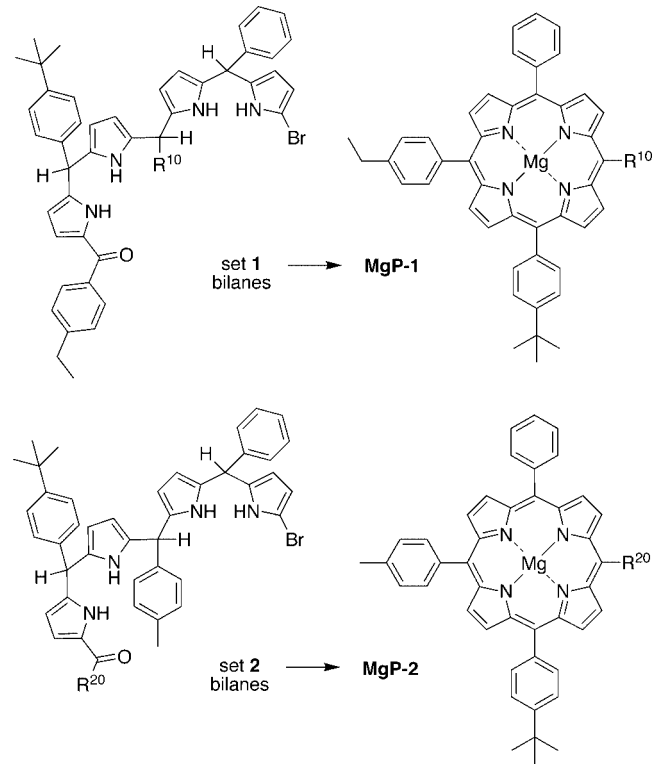
The paper is divided into three parts. In part I, we describe the synthesis of 1-bromo-9-acyldipyrromethanes and 1-acyldipyrromethanes, and their elaboration to the corresponding bilanes under acid-catalyzed condensation. Part II describes the one-flask conversion of the 1-bromo-19-acylbilanes to the corresponding ABCD-porphyrins. In part III, the findings from the prior sections are applied in the synthesis of two types of porphyrins: (i) porphyrins bearing three pyridyl groups and (ii) tetraalkylporphyrins. The study reveals information concerning the types of *meso*-substituted bilanes and porphyrins that can be synthesized via this new methodology.

Results and Discussion

I. Synthesis of Bilanes. The groups chosen to explore the scope of the methodology include alkyl (pentyl), electron-withdrawing (pentafluorophenyl), electron-releasing (4-methoxyphenyl), heterocyclic (4-pyridyl), bulky (mesityl), alkyl ester (3-methoxy-3-oxopropyl), and no substituent (−H). In this study, two sets of bilanes were prepared. In the first set, all bilanes vary only at the 10-position, whereas in the second set, all bilanes vary only at the 20-position. Such variation is achieved by condensation of a series of 1-bromodipyrromethane-9-carbinols with a 1-acyldipyrromethane. The invariant (5-, 15-) substituents are identical with that of the benchmark bilane **1a** (vide infra), namely phenyl and 4-*tert*-butylphenyl, whereas 4-methylphenyl (10-position) or 4-ethylphenyl (20-position) is swapped out in bilane set **1** or **2**, respectively. The two sets of bilanes (**1**, **2**) and the corresponding magnesium porphyrins (**MgP-1**, **MgP-2**) are shown in Chart 1.

A. Preparation of Dipyrromethane Species. Established routes were followed to obtain the dipyrromethane species required herein, a sizable number of which are known compounds. Multigram quantities of 5-phenyldipyrromethane **3a**[15] and 5-(4-*tert*-butylphenyl)dipyrromethane **3b**[12] were synthesized by condensation of the corresponding aldehyde with excess pyrrole.[15] Dipyrromethane **3a** was acylated[16] with known Mukaiyama reagents (**4a**,[17] **4b**,[13] **4c**,[17] **4d**,[17] **4e**,[13] **4f**[13]) to give the corresponding 1-acyldipyrromethanes **5a**−**f** in 71−93% yield (Table 1, entries 1−6), of which **5a**,[16] **5b**−**d**,[18] and **5e**[7] are known compounds (**5b**−**e** were prepared previously by a different route). The acylation[17] of **3a** with 2,4,6-trimethylbenzoyl chloride (**4g**) afforded the corresponding 1-acyldipyrromethane **5g**[18] in 21% yield (entry 7). Formylation[14] of **3a** with the Vilsmeier reagent (**4h**) afforded **5h**[19] in 43% yield (entry 8). The 1-acyldipyrromethanes **5a**−**h** were subjected to regioselective α-bromination[20,21] with NBS to give 1-bromo-9-acyldipyrromethanes **5a**−**h-Br** in 54−92% yield (Table 1, entries 1−8), of which **5a-Br**[18] is a known compound. The variation in yield is believed to stem from differences in stability and ease of purification of each product. The resulting 1-bromo-9-acyldipyrromethanes constitute precursors for the AB-half of each bilane.

CHART 1



The precursors for the CD-half of each bilane were derived by acylation of dipyrromethane **3b** in the same manner as for dipyrromethane **3a**. The acylations entailed use of Mukaiyama reagents **4i**[12] (Table 2, entry 1) and **4b**−**f** (entries 2−6), 2,4,6-trimethylbenzoyl chloride (entry 7), and the Vilsmeier reagent (entry 8). In so doing, new 1-acyldipyrromethanes **6a**−**h** were obtained in 27−66% yield.

B. Bilane Formation. We followed the protocol[12] employed previously for the synthesis of the target bilanes: (i) each 1-bromo-9-acyldipyrromethane (**5a**−**h-Br**) was reduced to the corresponding carbinol (**5a**−**h-Br-OH**) in THF/MeOH (3:1) with $NaBH_4$. Each crude carbinol (**5a**−**h-Br-OH**, 0.5 M) was condensed with a 1-acyldipyrromethane (**6a**−**h**, 0.5 M) in CH_3CN/MeOH (3:1) containing $Yb(OTf)_3$ (3.3 mM) at room temperature. In most cases, after 2 h of condensation, TLC analysis of the crude reaction mixture revealed complete consumption of the carbinol, a trace of unreacted 1-acyldipyrromethane (**6a**−**h**), and the corresponding bilane (**1a**−**h**). Workup entailed quenching with excess triethylamine followed by column chromatography. For the preparation of bilane set **1** (R^{10} variation), 1-acyldipyrromethane **6a** was condensed with each of the 1-bromodipyrromethane-9-carbinols **5a**−**h-Br-OH** to give bilanes **1a**−**h**. For set **2** (R^{20} variation), each of the 1-acyldipyrromethanes **6b**−**h** was condensed with 1-bromodipyrromethane-9-carbinol **5a-Br-OH** to give bilanes **2b**−**h**.

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(16) Rao, P. D.; Littler, B. J.; Geier, G. R., III; Lindsey, J. S. *J. Org. Chem.* **2000**, *65*, 1084–1092.
(17) Zaidi, S. H. H.; Muthukumaran, K.; Tamaru, S.-I.; Lindsey, J. S. *J. Org. Chem.* **2004**, *69*, 8356–8365.
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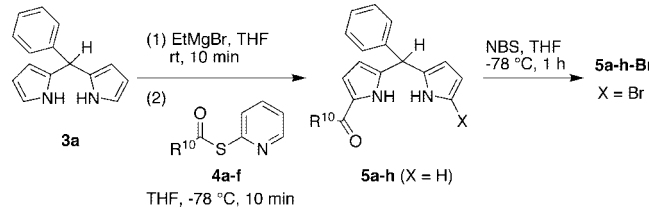
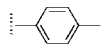
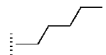
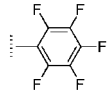
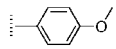
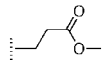
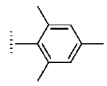
TABLE 1. Synthesis of 1-Bromo-9-acyldipyrromethanes



Entry	4	R^{10}	5	Yield (%)	5-Br	Yield (%)
1	**4a**		**5a**	83[a]	**5a-Br**	92[b]
2	**4b**		**5b**	72	**5b-Br**	63
3	**4c**		**5c**	93	**5c-Br**	69
4	**4d**		**5d**	83	**5d-Br**	84
5	**4e**		**5e**	71	**5e-Br**	88
6	**4f**		**5f**	72	**5f-Br**	Mixture[c]
7	**4g**[d]		**5g**	21	**5g-Br**	58
8	**4h**[e]		**5h**	43	**5h-Br**	54

[a] Reference 16. [b] Reference 18. [c] Inseparable mixture of 1-bromo and 2-bromo-9-acyldipyrromethanes. [d] Acylation was performed with 2,4,6-trimethylbenzoyl chloride.[17] [e] Via Vilsmeier formylation.[14]

The results are displayed in Table 3. Application of the standard method only worked well in the first set of bilanes (entries 1−8) in three cases (**1a**, **1b**, **1d**), but afforded good yields for all members of the second set of bilanes (**2b**−**h**; entries 9−15). In the first set of bilanes, the R^{10} substituent is varied, and reaction must occur at this (carbinol) site for bilane formation. By contrast, in the second set of bilanes, the R^{20} substituent is varied, which does not participate in bilane formation. Modified conditions for bilane formation were investigated where reaction failed as described in the following.

(i) R^{10} = Pentafluorophenyl (1c). Only a trace of **1c** was observed after 8 h under the standard conditions. Upon increasing the concentration of $Yb(OTf)_3$ to 23 mM (while maintaining the 3:1 ratio of CH_3CN/MeOH), after 30 min the resulting heterogeneous reaction mixture contained the bilane **1c**, a trace amount of unreacted **6a**, and a polar unidentified component (TLC analysis). Alternatively, the concentration of $Yb(OTf)_3$ was maintained at 3.3 mM while carrying out the reaction in acetonitrile in the absence of methanol. After 5 h, TLC analysis revealed complete consumption of **5-c-Br-OH**, a trace amount of **6a**, and bilane **1c**. Subsequent workup afforded bilane **1c** in 87% yield (Table 3, entry 3).

(ii) R^{10} = 4-Pyridyl (1e). No bilane was observed after 5 h under the standard conditions, or upon increasing the concentration of $Yb(OTf)_3$ to 23 mM. Upon increasing the concentration of acid to 230 mM in acetonitrile in the absence of methanol, reaction proceeded in 3 h to give bilane **1e** together with two more polar, unidentified products. MALDI-MS analysis revealed the molecule ion peak expected for bilane **1e** together with multiple peaks, none of which was consistent with any scrambling processes. The standard workup and purification with column chromatography afforded the target bilane **1e** in 36% yield (Table 3, entry 5).

Because the incorporation of heterocyclic substituents in distinct patterns has presented notorious difficulties in porphyrin synthesis,[2,13,22–24] we also examined several other mild Lewis acid catalysts [$Zn(OTf)_2$, $InCl_3$, $Er(OTf)_3$, and $Bi(OTf)_3$] over a range of concentrations (3.30, 23.0, and 230 mM) in neat acetonitrile for the synthesis of **1e**. $Zn(OTf)_2$ gave no product even after overnight stirring at room temperature. $InCl_3$, $Er(OTf)_3$, and $Bi(OTf)_3$ at 230 mM each afforded the target bilane upon 6−8 h of reaction. The cleanest reaction was

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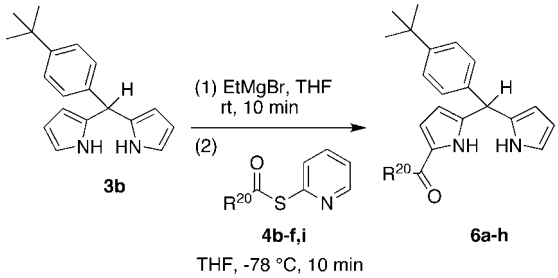
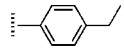
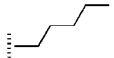
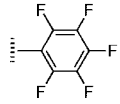
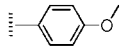
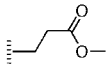
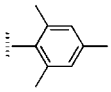
TABLE 2. Synthesis of 1-Acyldipyrromethanes



Entry	4	R^{20}	6	Yield (%)
1	**4i**		**6a**[a]	66
2	**4b**		**6b**	52
3	**4c**		**6c**	41
4	**4d**		**6d**	56
5	**4e**		**6e**	52
6	**4f**		**6f**	65
7	**4g**[b]		**6g**	33
8	**4h**[c]		**6h**	27

[a] Ref 12. [b] Acylation was performed with 2,4,6-trimethylbenzoyl chloride. [c] Via Vilsmeier formylation.

observed with $InCl_3$ (no starting materials remained). The success of these reaction conditions augurs well for the synthesis of elaborate bilanes bearing heterocyclic substituents.

(iii) R^{10} = 3-Methoxy-3-oxopropyl (1f). The reduction of the ketone in **5f-Br** to give **5f-Br-OH** proceeded smoothly; however, the standard condensation protocol afforded three new components, but no bilane was detected by MALDI-MS or by ^1H NMR spectroscopy (entry 6). The origin of this surprising failure is not known, but may stem from chelation of magnesium by the ester and the α-carbinol moieties.

(iv) R^{10} = Mesityl (1g). All attempts to reduce the mesitoyl group of **5g-Br** failed to give the corresponding carbinol **5g-Br-OH** (entry 7). The conditions examined include use of excess $NaBH_4$ (100 mol equiv versus **5g-Br**, 8.25 mM) in anhydrous THF/MeOH (2:1),[25] twice this amount of $NaBH_4$, or $LiBH_4$.

(v) R^{10} = H (1h). The reaction of **5h-Br-OH** and **6a** under standard conditions afforded three components (a streaking component, unreacted **6a**, and a polar material). Standard workup gave mostly decomposition products rather than the desired bilane (entry 8).

In summary, modified acid-catalysis conditions proved useful for dipyrromethane-carbinols bearing pentafluorophenyl or *p*-pyridyl groups at the carbinol site. The origin of use of the mixed solvent CH_3CN/MeOH (3:1) stemmed from use of the acid in a stock solution of methanol, which afforded higher solubility of the acid than neat acetonitrile.[12] Neat acetonitrile was employed here to avoid competition of the acid for the hydroxy group of methanol versus the hydroxy group of the dipyrromethane-carbinol. [Note that in the absence of methanol, the acid catalyst is not entirely dissolved (the reaction mixture is heterogeneous), yet we maintain use of the concentration term (e.g., 230 mM) for consistency and purposes of comparison.] Regardless of solvent, bilanes bearing a 10-mesityl group or no substituent (R^{10} = H) cannot be prepared via this approach. The bilanes were characterized by NMR spectroscopy (^1H, ^{13}C) and mass spectrometry (MALDI-MS, ESI-MS).

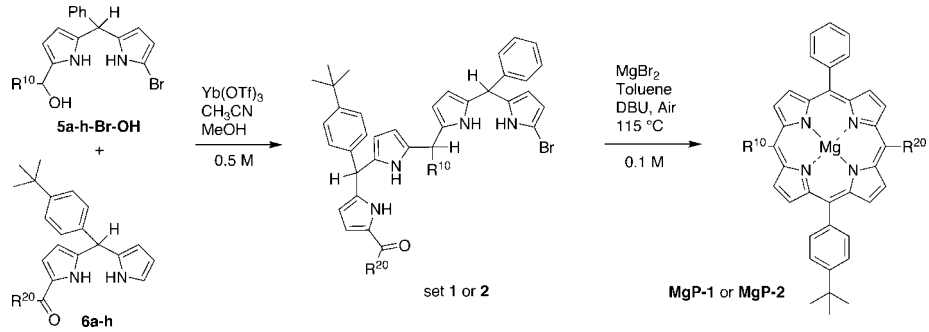
II. Synthesis of Metalloporphyrins from Bilanes. The synthesis of ABCD-porphyrins was carried out by using bilanes that possess a variety of substituents at the 10-position (set **1**: **1a**−**e**) and 20-position (set **2**: **2b**−**h**). The standard protocol[12] entails the bilane (100 mM) in toluene (115 °C) containing DBU (10 mol equiv versus the bilane) and $MgBr_2$ (3 mol equiv versus the bilane) with exposure to air. The results are displayed in Table 3. Of 11 new trials (**MgP-1a**[12] was made previously), nine ABCD-porphyrins were obtained in yields of 17−60% in 2−4 h.

The standard reaction with bilane **2h** to obtain ABC-porphyrin **MgP-2h** (which contains one unsubstituted *meso* position) afforded an inseparable mixture of porphyrin and chlorin as evidenced by absorption spectroscopy (λ_{abs} = 624 nm, consistent with expectation for a magnesium-triarylchlorin[26,27]) and laser-desorption mass spectrometry (LD-MS) in the absence of a matrix[28] (Table 3, entry 15). A traditional method for handling such mixtures entails DDQ-mediated oxidation to convert chlorin to porphyrin;[29–31] however, treatment of the mixture gave an unknown byproduct in low yield rather than the desired porphyrin. *Meso*-unsubstituted porphyrins are known to be susceptible to reactions at the unsubstituted *meso* site, particularly upon oxidation to give *meso*,*meso*-linked dimers.[32] Given that magnesium porphyrins are more susceptible to one-electron oxidation than zinc porphyrins,[33] and zinc reagents have been employed in place of $MgBr_2$ in the conversion of bilane to porphyrin,[12] we carried out the macrocycle-forming reaction in the presence of $Zn(OAc)_2$. The use of $Zn(OAc)_2$ with bilane **2h** afforded a lesser amount of chlorin (λ_{abs} = 620 nm), and upon oxidation with DDQ, the target zinc ABC-porphyrin **ZnP-2h** was obtained in 25% yield.

An alternative approach to prepare ABC-porphyrins was investigated by the reaction of 1-formyl-9-bromodipyrromethane **5h-Br** (without reduction) and 1-acyldipyrromethane **6a** to give the bilene-*b* intermediate. This approach was pursued because

(25) Decréau, R. A.; Collman, J. P. *Tetrahedron Lett.* **2003**, *44*, 3323–3327.
(26) Taniguchi, M.; Kim, M. N.; Ra, D.; Lindsey, J. S. *J. Org. Chem.* **2005**, *70*, 275–285.
(27) Taniguchi, M.; Ptaszek, M.; McDowell, B. E.; Boyle, P. D.; Lindsey, J. S. *Tetrahedron* **2007**, *63*, 3850–3863.
(28) Srinivasan, N.; Haney, C. A.; Lindsey, J. S.; Zhang, W.; Chait, B. T. *J. Porphyrins Phthalocyanines* **1999**, *3*, 283–291.
(29) Barnett, G. H.; Hudson, M. F.; Smith, K. M. *Tetrahedron Lett.* **1973**, *14*, 2887–2888.
(30) Rousseau, K.; Dolphin, D. *Tetrahedron Lett.* **1974**, *15*, 4251–4254.
(31) Barnett, G. H.; Hudson, M. F.; Smith, K. M. *J. Chem. Soc., Perkin Trans. 1* **1975**, 1401–1403.
(32) Kamo, M.; Tsuda, A.; Nakamura, Y.; Aratani, N.; Furukawa, K.; Kato, T.; Osuka, A. *Org. Lett.* **2003**, *5*, 2079–2082.
(33) Fuhrhop, J.-H.; Mauzerall, D. *J. Am. Chem. Soc.* **1969**, *91*, 4174–4181.

TABLE 3. Synthesis of Bilanes (1, 2) and ABCD-Porphyrins (MgP-1, MgP-2)



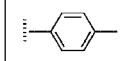
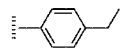
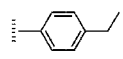
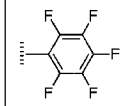
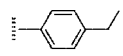
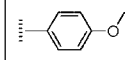
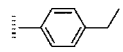
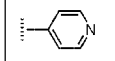
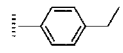
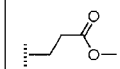
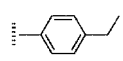
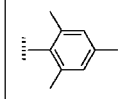
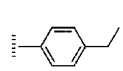
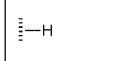
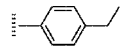
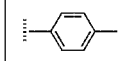
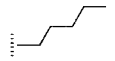
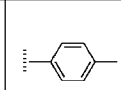
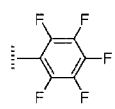
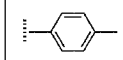
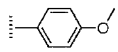
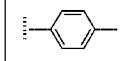
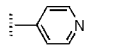
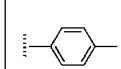
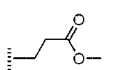
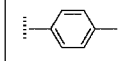
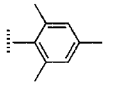
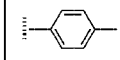
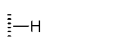
Entry	Reactants		R^{10}	R^{20}	**Bilane**[a]	Yield (%)	**Porphyrin**[b]	Yield (%)
1[c]	**5a-Br-OH**	**6a**			**1a**	76	**MgP-1a**	69
2	**5b-Br-OH**	**6a**			**1b**	85	**MgP-1b**	46
3	**5c-Br-OH**	**6a**			**1c**	87[d]	**MgP-1c**	29[e]
4	**5d-Br-OH**	**6a**			**1d**	76	**MgP-1d**	45
5	**5e-Br-OH**	**6a**			**1e**	36[d,f]	**MgP-1e**	57
6	**5f-Br-OH**	**6a**			**1f**	0	**MgP-1f**	NA
7	**5g-Br-OH**	**6a**			**1g**	0[g]	**MgP-1g**	NA
8	**5h-Br-OH**	**6a**			**1h**	0[h]	**MgP-1h**	NA
9	**5a-Br-OH**	**6b**			**2b**	57	**MgP-2b**	37
10	**5a-Br-OH**	**6c**			**2c**	35	**MgP-2c**	42[e]
11	**5a-Br-OH**	**6d**			**2d**	64	**MgP-2d**	60
12	**5a-Br-OH**	**6e**			**2e**	61	**MgP-2e**	54
13	**5a-Br-OH**	**6f**			**2f**	68	**MgP-2f** **P-2f-OH**[i]	17 4
14	**5a-Br-OH**	**6g**			**2g**	64	**MgP-2g**	<2
15	**5a-Br-OH**	**6h**			**2h**	56[j]	**MgP-2h** **ZnP-2h**	0[k] 25[l]

TABLE 3. Continued

[a] The bilanes were prepared with 1 or 0.5 mmol of each reactant in CH_3CN/MeOH (3:1) containing $Yb(OTf)_3$ (3.3 mM) in 2−5 h at room temperature (Method 3). [b] Each porphyrin was prepared by reaction of a bilane in toluene containing $MgBr_2$ and DBU exposed to air under conventional heating (Method 4). [c] Reference 12. [d] Performed in CH_3CN without MeOH. [e] A more polar porphyrin, a putative covalent adduct with DBU, was isolated in ~6% yield. [f] Perfomed with 230 mM $Yb(OTf)_3$. [g] The reduction of **5g-Br** was not successful. [h] **5h-Br-OH** decomposed during bilane formation (Method 1). [i] The free base porphyrin bearing a carboxylic acid (rather than an ester). [j] Performed with 23 mM $Yb(OTf)_3$ at 55 °C. [k] An inseparable mixture of porphyrin and chlorin was obtained. [l] Performed with $Zn(OAc)_2$ in place of $MgBr_2$.

(i) chlorin contaminants are believed to derive upon tautomeric rearrangement of polypyrromethane precursors (e.g., porphyrinogens),[34] (ii) we felt that preformation of the unsaturated unit at the position lacking an aryl substituent (i.e., the 10-position) would thereby avoid tautomeric rearrangement at this apparently problematic site, and (iii) the requisite 1-bromo-9-formyldipyrromethanes have been used successfully in analogous condensations in chlorin chemistry.[21,35] The reaction with the standard acid-catalysis conditions with $Yb(OTf)_3$ was sluggish and required mild heating (55 °C) for 2 h to give the bilene (λ_{max} = 490 nm), whereas the same reaction could be carried out in 30 min with *p*-toluenesulfonic acid at room temperature. Subsequent treatment of the bilene to the porphyrin-forming conditions indeed gave **MgP-2i** in 11% yield (Scheme 3). On the other hand, prolonged heating of the reaction mixture in air gave the corresponding *meso*,*meso*-linked porphyrin dimer.

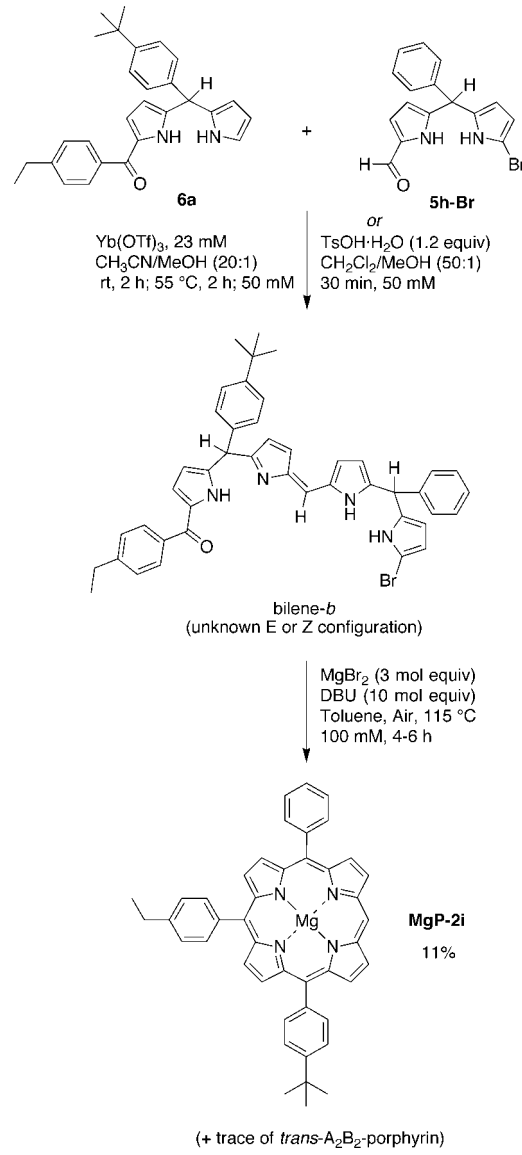
III. Applications. The scope was explored further by preparation of bilanes and porphyrins bearing three pyridyl groups or four alkyl groups. In this study, the substituent variation was focused at the R^5, R^{15}, and R^{20} sites while maintaining the R^{10} substituent of a type that is known to afford successful reaction in bilane formation.

A. Porphyrins Bearing Three Pyridyl Substituents. (i) Bilane Synthesis. We investigated the synthesis of target molecules bearing three heterocyclic substituents (*o*-, *m*-, *p*-pyridyl). In each target bilane, the R^5 substituent was *m*-pyridyl, the R^{10} substituent was 4-ethylphenyl, and the 15- and 20-positions were varied (*o*-, *m*-, *p*-pyridyl). The synthesis of each bilane employed 1-bromodipyrromethane-9-carbinol **7-Br-OH**, which was prepared as shown in Scheme 4. The dipyrromethane bearing a *m*-pyridyl group (**3c**)[22] was treated with Mukaiyama reagent **4i** to give the corresponding 1-acyldipyrromethane **7** in 42% yield. α-Bromination[20,21] of the latter afforded 1-acyl-9-bromodipyrromethane **7-Br** in 79% yield. Reduction with $NaBH_4$ gave **7-Br-OH**, which constitutes the precursor for the AB-half of each bilane, in clean fashion (one new component by TLC analysis).

The bilane synthesis entailed condensation of the carbinol **7-Br-OH** with a 1-acyldipyrromethane (0.5 M each) in neat acetonitrile (without methanol) containing $Yb(OTf)_3$ (230 mM). The rationale for the use of neat acetonitrile stemmed from our findings that bilanes that contain a heterocyclic group (**1e**, *p*-pyridyl) or a bulky electron-withdrawing substituent (**1c**, pentafluorophenyl) at the 10-position are formed faster and in higher yield upon reaction in neat acetonitrile. Each of the four 1-acyldipyrromethanes (**8a**−**d**) employed bears two pyridyl groups and is a known compound[13] (Table 4).

In each bilane-forming reaction, chromatographic purification proved difficult given the tendency of the tripyridyl-substituted bilanes to streak. In each case, TLC analysis of the purified fraction revealed one component; however, ^1H NMR spectroscopy showed the presence of the target bilane and an unidentified impurity. Although the 1-acyldipyrromethane generally was not detected, its presence was ostensibly revealed upon subsequent porphyrin formation. Our prior studies have shown that prolonged chromatographic purification of a bilane results in formation of a green byproduct, presumably owing to oxidation.[12] Accordingly, in each case the crude bilane was carried on to the porphyrin-forming reaction without further purification.

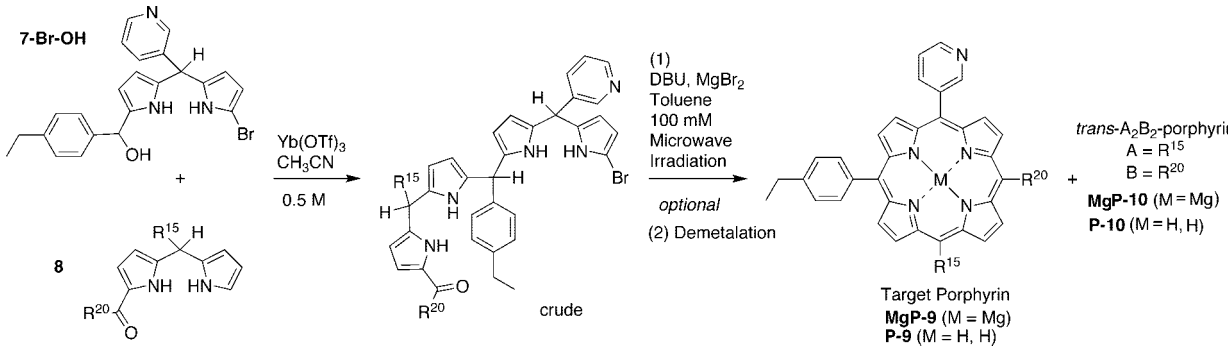
SCHEME 3



(ii) Porphyrin Synthesis. Microwave irradiation can provide a superior method versus conventional heating for the synthesis of porphyrins bearing heterocyclic substituents.[13] Accordingly, in each case the crude bilane was subjected to the porphyrin-

(34) Dolphin, D. *J. Heterocycl. Chem.* **1970**, *7*, 275–283.
(35) Laha, J. K.; Muthiah, C.; Taniguchi, M.; McDowell, B. E.; Ptaszek, M.; Lindsey, J. S. *J. Org. Chem.* **2006**, *71*, 4092–4102.

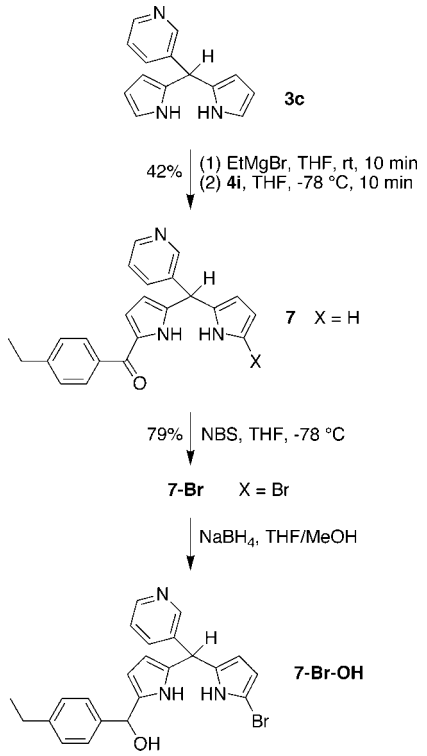
TABLE 4. Porphyrins Bearing Three Pyridyl Substituents[a]



R^{15}	R^{20}	Cmpd **8**	Target Porphyrin	Type	M	Yield (%)	*trans*-A_2B_2-Porphyrin	Yield (%)
		**8a**	**MgP-9a**	*trans*-AB_2C	Mg	12	**MgP-10a**	trace
		**8b**	**MgP-9b**	A_3B	Mg	8	**MgP-10b**	trace
		**8c**	**P-9c**	*trans*-AB_2C	H, H[b]	17	**P-10c**	7
		**8d**	**P-9d**	ABCD	H, H[b]	25	**P-10d**	15

[a] The bilane and the porphyrin were prepared following Method 5 (see text). Microwave irradiation was used in each porphyrin-forming reaction. [b] Demetalation was performed.

SCHEME 4



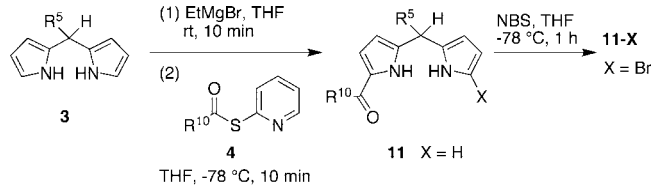
forming conditions [DBU (10 mol equiv) and $MgBr_2$ (3 mol equiv) in toluene] via microwave irradiation. In each case, the TLC and LD-MS analyses of the crude reaction mixture revealed the presence of two porphyrin products, the target porphyrin and a *trans*-A_2B_2-porphyrin. The *trans*-A_2B_2-porphyrin is believed to derive from the condensation of unreacted 1-acyldipyrromethane (**8**) that was present as a contaminant in the crude bilane.

The results are shown in Table 4. Porphyrin **MgP-9a** contains an *o*-pyridyl group flanked by two *m*-pyridyl groups (*trans*-AB_2C-porphyrin) and was isolated in 12% yield. Porphyrin **MgP-9b** contains three *m*-pyridyl groups (A_3B-porphyrin) and was obtained in 8% yield upon alumina column chromatography. In each case, a trace of the *trans*-A_2B_2-porphyrin (**MgP-10a**, **MgP-10b**) also was isolated.

The chromatographic purification of the magnesium porphyrin was not successful in the case of putative **MgP-9c** and **MgP-9d**, each of which bears one *p*-pyridyl group and two other pyridyl groups. Hence, demetalation was performed and the target porphyrin was isolated as the free base. Thus, free base porphyrin **P-9c** contains a sequence of *m*-, *p*-, and *m*-pyridyl groups (*trans*-AB_2C-porphyrin) and was isolated in 17% yield accompanied by the free base *trans*-A_2B_2-porphyrin **P-10c** in 7% yield. (For comparison, the yield of each porphyrin **P-9c** and **P-10c** is based on the theoretical yield of the target bilane.) Similarly, free base porphyrin **P-9d**, which contains a sequence of *m*-, *o*-, and *p*-pyridyl groups (ABCD-porphyrin), was isolated in 25% yield accompanied by the free base *trans*-A_2B_2-porphyrin **P-10d** in 15% yield. The synthetic approach affords the desired pyridyl-porphyrins in low yield but provides a viable complement to existing rational methods[2,13,22–24] for preparing porphyrins bearing distinct patterns of pyridyl substituents.

B. Tetraalkylporphyrins. The synthesis of porphyrins bearing four *meso*-alkyl groups also was examined. A variety of *meso*-alkyl/aryl-porphyrins have been prepared;[7,36–38] however,

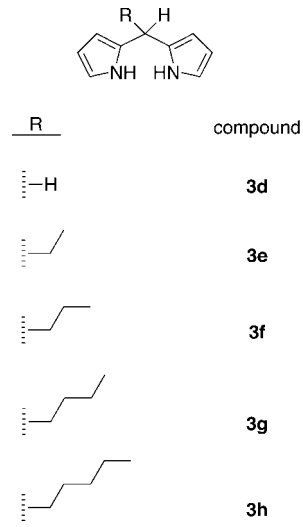
TABLE 5. Synthesis of Alkyl-Substituted 1-Acyldipyrromethanes



Entry	3	4	R^5	R^{10}	11	Yield (%)
1	**3d**	**4j**	–H		**11a**	42
2	**3e**	**4j**			**11b**	81[a]
					11b-Br	88
3	**3e**	**4k**			**11c**	64
					11c-Br	89
4	**3e**	**4l**			**11d**	62
					11d-Br	94
5	**3f**	**4l**			**11e**	46[a]
6	**3f**	**4b**			**11f**	52
7	**3g**	**4b**			**11g**	79
8	**3h**	**4b**			**11h**	65[b]
					11h-Br	85

[a] Reference 13. [b] Reference 46.

CHART 2



the most elaborate *meso*-tetraalkylporphyrins prepared to date apparently are limited to A_4-[39–42] and A_3B-substituent[43] patterns. The dipyrromethanes used are shown in Chart 2.

All of the dipyrromethanes are known compounds; those bearing the *meso* substituent H (**3d**),[15] ethyl (**3e**),[13] propyl (**3f**),[13] and pentyl (**3h**)[15] were prepared previously by condensation with pyrrole in the presence of $InCl_3$. 5-Butyldipyrromethane (**3g**), previously described without complete characterization,[44,45] was prepared herein by reaction with pyrrole containing $InCl_3$. A new Mukaiyama reagent, *S*-2-pyridyl butanothioate (**4k**), was prepared by reaction of 2-mercaptopyridine and butyryl chloride.

A series of 1-acyldipyrromethanes was prepared as shown in Table 5. The reaction of dipyrromethanes **3d**−**h** with the Mukaiyama reagents **4b**, **4j**,[13] **4k**, and **4l**[13] following the standard acylation procedure[16] afforded the target 1-acyldipyrromethanes in 42−79% yields, of which **11b**,[13] **11e**,[13] and **11h**[46] are known compounds. 1-Acyldipyrromethanes **11b**−**d** and **11h** were subjected to regioselective α-bromination[20,21] with NBS to afford the corresponding 1-bromo-9-acyldipyrromethanes (Table 5). Compound **11c-Br** was very unstable and underwent discoloration upon warming a stored sample above −4 °C. Surprisingly, the analogous compound **11d-Br** was sufficiently stable to obtain full characterization data (^{1}H NMR and ^{13}C NMR spectra in THF-d_8, ESI-MS, and elemental analysis).

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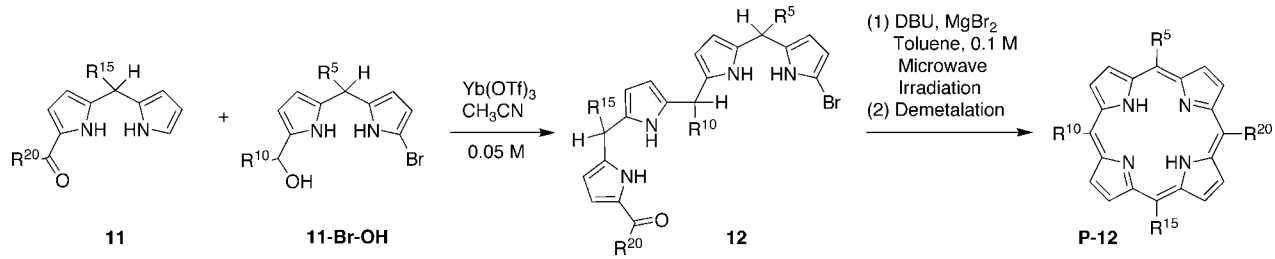
TABLE 6. Bilanes and Porphyrins Bearing Alkyl Substituents[a]



Entry	11-Br-OH	11	R^5	R^{10}	R^{15}	R^{20}	Bilane	Yield (%)	Porphyrin	Type	Yield (%)
1	**11h-Br-OH**	**11b**					**12a**	37	**MgP-12a**	*cis*-A_2B_2	16[b]
2	**11b-Br-OH**	**11a**			—H		**12b**	86	**P-12b**	A_3	--[b]
3	**11h-Br-OH**	**11a**			—H		**12c**	62	**P-12c**	*cis*-A_2B	16[c]
4	**11d-Br-OH**	**11e**					**12d**	78	**P-12d**	*trans*-AB_2C	23
5	**11d-Br-OH**	**11f**					**12e**	63	**P-12e**	ABCD	18
6	**11c-Br-OH**	**11g**					**12f**	81	**P-12f**	ABCD	24

[a] The bilane was prepared in CH_3CN containing $Yb(OTf)_3$ (3.3 mM) for 30 min at room temperature (Method 6). Each porphyrin was prepared by reaction of a bilane in toluene containing $MgBr_2$ and DBU exposed to air under microwave irradiation unless noted otherwise. [b] By use of conventional heating (Method 4; no demetalation, giving the magnesium chelate). [c] No porphyrin was obtained upon conventional heating.

The bilane synthesis was performed under conditions slightly modified from the standard protocol given that all of the dialkyl 1-bromo-9-acyldipyrromethane-carbinols were found to be unstable in the solid form. Reduction of a dialkyl 1-bromo-9-acyldipyrromethane (**11b-Br**, **11c-Br**, **11d-Br**, **11h-Br**) was carried out in the standard way with excess $NaBH_4$ to give the corresponding carbinol. The modifications to the procedure were as follows: (i) the dipyrromethane-carbinol was concentrated in a mixture of ethyl ether/acetonitrile (1:5) until most of the ether was removed, (ii) the resulting carbinol was used directly in the bilane-forming reaction, and (iii) acid-catalyzed condensation was carried out at 0.05 M (rather than 0.5 M) in acetonitrile containing $Yb(OTf)_3$. Acetonitrile was used alone (without methanol) in conjunction with the lower reaction concentration, and in preliminary experiments with alkyl-substituted substrates was found to support reactions with good yields. In this manner, the subsequent standard workup with chromatography afforded the target tetraalkylbilanes in 62−86% yields (Table 6).

Treatment of tetraalkyl-substituted bilane **12a** to the reaction conditions (including conventional heating for 8 h) gave the target *cis*-A_2B_2-porphyrin **MgP-12a** in 16% yield. However, attempts to perform the reaction of bilane **12b** or **12c** under conventional heating gave no porphyrin. The promising results obtained for the synthesis of porphyrins bearing heterocyclic substituents under microwave irradiation[13] encouraged the analogous synthesis of tetraalkylporphyrins. Thus, a given bilane (**12c−f**) was treated with DBU (10 mol equiv) and $MgBr_2$ (3 mol equiv) in toluene (Table 6). The reaction mixture was subjected to microwave irradiation for 30 min. In each case, examination of the crude reaction mixture by absorption spectroscopy showed the characteristic porphyrin Soret band and two broad peaks (303 and 525 nm; unassigned origin). TLC analysis showed consumption of the bilane, formation of the porphyrin, and a polar tailing component. Microwave irradiation was continued (typically 36 h) until TLC analysis and absorption spectroscopy did not show any intermediate. The crude reaction mixture was subjected to demetalation followed by column chromatography. In each case, the porphyrin was obtained in yields ranging from 16% to 24%. The resulting porphyrins include two ABCD-porphyrins (**P-12e**, **P-12f**), each of which contains an ethyl, propyl, butyl, and pentyl group (and hence are isomers), and one *trans*-AB_2C-porphyrin (**P-12d**).

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Outlook

The data obtained herein provide extensive information concerning the scope of the route to ABCD-bilanes and ABCD-porphyrins. The key findings are as follows:

(1) The pentyl unit gave better yields at the 20- versus 10-position in both bilane and porphyrin formation (Table 3, entries 2 and 9).

(2) The pentafluorophenyl unit at the 10- versus 20-position of the bilane gave somewhat better yields upon bilane formation (Table 3, entries 3 and 10), but the reverse was observed in porphyrin formation.

(3) The 4-methoxyphenyl group at the 20- versus 10-position of the bilane resulted in a higher yield in the porphyrin-forming reaction (Table 3, entries 4 and 11).

(4) No significant difference in porphyrin yield was observed by having the 4-pyridyl group at the 10- or 20-position of the bilane (Table 3, entries 5 and 12).

(5) An alkyl ester unit can be introduced to the porphyrin macrocycle via the 20- but not the 10-position of the bilane (Table 3, entries 6 and 13).

(6) A mesityl group cannot be introduced at the 10-position of the bilane, and a 20-mesityl-substituted bilane does not give significant amounts of the porphyrin (Table 3, entries 7 and 14).

(7) A 10-unsubstituted porphyrin can be prepared via a bilene-*b* (but not a bilane) because a dipyrromethane containing a primary carbinol does not give the bilane (Table 3, entry 8; Scheme 3).

(8) A 20-unsubstituted porphyrin can be prepared as the zinc but not the magnesium chelate (Table 3, entry 15).

(9) The synthesis of sparsely substituted alkylporphyrins via conventional heating was rather unsuccessful but could be achieved via microwave irradiation (Table 6, entries 2 and 3).

(10) Bilanes and porphyrins bearing up to three different pyridyl groups in distinct arrangements can be prepared (Table 4). A change in the ratio of reagents was not necessary for successful reaction despite the presence of three alternative coordination sites (in addition to the acyl moiety) for the acid catalyst or $MgBr_2$ in the reacting species.

(11) Bilanes and porphyrins bearing up to four different alkyl groups can be prepared (Table 6).

(12) The 1-bromo-19-acylbilanes bearing aryl or heteroaryl substituents were stable to routine handling on the open benchtop and upon prolonged storage at −4 °C. By contrast, the analogous bilanes bearing alkyl substituents were rather unstable and were used shortly after preparation (see Supporting Information).

Alkyl and pyridyl groups were of particular interest in this study because both types of groups have afforded poor results with the standard dipyrromethane + dipyrromethane-dicarbinol route to ABCD-porphyrins.[2] The alkyl-substituted dipyrromethanes give rise to multiple porphyrin products (owing to acidolytic scrambling), whereas the pyridyl groups tend to complex with the acid catalysts and thereby impede the reaction. Extensive efforts have been devoted to the challenge of synthesizing porphyrins bearing distinct patterns of pyridyl substituents.[13,22–24] The new method for condensation of a 1-acyldipyrromethane (Scheme 2) to give *trans*-A_2B_2-porphyrins is broadly compatible with pyridyl substituents but only marginally so with alkyl groups; regardless, the route does not provide access to ABCD patterns for porphyrins, and offers no access to bilanes at all.[13] The conditions employed herein rely on (i) a mild Lewis acid in a polar medium [e.g., $Yb(OTf)_3$ in acetonitrile] for bilane formation and (ii) nonacidic conditions for macrocycle formation. The conditions support reaction in the presence of alkyl and pyridyl substituents without detectable scrambling. Thus, the new capabilities with pyridyl and alkyl groups fill longstanding lacunae in porphyrin chemistry.

The scope demonstrated herein is quite promising for a number of applications. The applications for the porphyrins are manifold, yet the bilanes may prove equally versatile. Almost all prior studies of bilanes have focused on naturally occurring analogues, which bear β-pyrrole substituents and lack *meso* substituents.[47–56] The bilanes (and their various oxidized analogues: bilenes, biladienes, and bilatrienes) may prove very attractive in studies of coordination chemistry, supramolecular chemistry, redox chemistry, materials chemistry, and photochemistry (as phytochrome or phycobilin analogues). Regardless of application, significant features of the route will require further development. One limitation is the necessity for elevated temperature to achieve macrocycle formation: the reaction proceeds well at ∼115 °C but poorly at lower temperatures. Much about scope remains to be determined, including the effects of ortho and meta substituents on *meso*-aryl groups, and the effects of diverse substituents at the 5- and 15-positions of the bilane and porphyrin. Much about the mechanism of macrocycle formation also remains unknown, particularly the nature of the reactive end groups (acylpyrrole and bromopyrrole) upon carbon−carbon bond formation, the nature of any metal-coordination complexes (i.e., templating), the course of oxidation prior to or following macrocycle formation, and the relative reactivity of the different (up to eight) stereoisomeric forms of the bilane. We note that while the reaction conditions and substrate in the macrocyclization are highly suggestive of metal templating, and the strategy was conceived with the notion that metal templating would facilitate macrocyclization, the reaction conditions also support facile metal (magnesium, zinc) insertion of free base porphyrins;[13,57] hence, the isolation of the metalloporphyrin is alone insufficient proof of metal templating. Gaining a deeper understanding of such mechanistic aspects of the reaction may lead to milder conditions for macrocycle formation and thereby further broaden the scope of application.

Experimental Section

5-Butyldipyrromethane (3g). Following a reported procedure,[15] a solution of valeraldehyde (5.31 mL, 50.0 mmol) in pyrrole (347 mL, 5.00 mol) at room temperature under argon was treated with

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$InCl_3$ (1.11 g, 5.00 mmol) for 1.5 h. Powdered NaOH (6.00 g, 150 mmol) was added. After being stirred for 1 h, the mixture was suction filtered. Excess pyrrole was removed from the filtrate under high vacuum, leaving a brown oil. Chromatography of the latter [silica, hexanes/CH_2Cl_2 (1:1) → (2:3)] afforded a yellow liquid (4.26 g, 42%): ^{1}H NMR δ 0.87 (t, J = 7.2 Hz, 3H), 1.25−1.33 (m, 4H), 1.91 (app q, J = 7.2 Hz, 2H), 3.90 (t, J = 7.6 Hz, 1H), 6.06−6.09 (m, 2H), 6.11−6.16 (m, 2H), 6.54−6.56 (m, 2H), 7.54−7.58 (br, 2H); ^{13}C NMR δ 14.3, 22.9, 30.0, 34.5, 37.8, 105.5, 108.2, 117.3, 133.7; ESI-MS obsd 202.14735, calcd 202.14700 ($C_{13}H_{18}N_2$). Anal. Calcd for $C_{13}H_{18}N_2$: C, 77.18; H, 8.97; N, 13.85. Found: C, 77.29; H, 8.99; N, 13.60.

***S*-2-Pyridyl Butanothioate (4k).** Following a reported procedure,[17] a solution of 2-mercaptopyridine (5.55 g, 50.0 mmol) in THF (50.0 mL) was treated slowly with butyryl chloride (5.33 g, 50.0 mmol). The resulting reaction mixture was stirred for 30 min. The reaction mixture was added to a biphasic solution of saturated aqueous $NaHCO_3$ (100 mL) and diethyl ether (100 mL). The mixture was stirred until the foaming subsided. The organic layer was extracted with diethyl ether. The organic extract was washed (water, brine), dried (Na_2SO_4), and concentrated to afford a yellow oil (8.066 g, 89%): ^{1}H NMR δ 0.99 (t, J = 7.4 Hz, 3H), 1.73−1.78 (m, 2H), 2.68 (t, J = 7.4 Hz, 2H), 7.26−7.29 (m, 1H), 7.61 (d, J = 7.4 Hz, 1H), 7.71−7.75 (m, 1H), 8.60−8.61 (m, 1H); ^{13}C NMR δ 13.7, 19.2, 46.2, 123.6, 130.3, 137.3, 150.6, 151.8, 196.6; ESI-MS obsd 181.05612, calcd 181.05613 ($C_9H_{11}NOS$). Anal. Calcd for $C_9H_{11}NOS$: C, 59.64; H, 6.12; N, 7.73. Found: C, 59.69; H, 6.10; N, 7.63.

General Protocol for the Synthesis of 1-Acyldipyrromethanes (Method 1). Following the standard procedure,[16] a solution of EtMgBr (19.0 mL, 19 mmol, 1.0 M in THF) was added slowly to a solution of a dipyrromethane (**3a**−**i**, 7.50 mmol) in THF (15.0 mL) under argon. The resulting mixture was stirred at room temperature for 10 min, and then cooled to −78 °C. A solution of a Mukaiyama reagent (**4a**−**d**,**4f**,**4i**−**l**, 7.50 mmol) in THF (15.0 mL) was added to the reaction mixture (**4e**[134] was added as a solid). The solution was stirred at −78 °C for 10 min, and then allowed to warm to room temperature. The reaction mixture was quenched by the addition of saturated aqueous NH_4Cl. The mixture was extracted with ethyl acetate. The organic layer was washed (water, brine), dried (Na_2SO_4), and filtered. The filtrate was concentrated. Column chromatography [silica, CH_2Cl_2 (until all the unreacted dipyrromethane was eluted) → hexanes/ethyl acetate (3:1)] afforded the corresponding 1-acyldipyrromethane.

1-(4-Ethylbenzoyl)-5-(3-pyridyl)dipyrromethane (7). Following Method 1, a solution of EtMgBr (10.0 mL, 10. mmol, 1.0 M in THF) was added to a solution of **3c** (0.893 g, 4.00 mmol) in THF (8.0 mL). A solution of **4i** (0.973 g, 4.00 mmol) in THF (8.0 mL) was added to the reaction mixture. The resulting crude product was chromatographed [silica, CH_2Cl_2/ethyl acetate (3:2) → CH_2Cl_2/ethyl acetate (1:1) → ethyl acetate] to afford a light-brown foam (0.594 g, 42%): mp 68−70 °C; ^{1}H NMR δ 1.27 (t, J = 7.6 Hz, 3H), 2.72 (q, J = 7.6 Hz, 2H), 5.57 (s, 1H), 5.93−5.96 (m, 1H), 6.07−6.09 (m, 1H), 6.12−6.14 (m, 1H), 6.69−6.70 (m, 1H), 6.79−6.81 (m, 1H), 7.12−7.16 (m, 1H), 7.28 (d, J = 7.8 Hz, 2H), 7.47−7.49 (m, 1H), 7.72 (d, J = 7.8 Hz, 2H), 8.39−8.42 (m, 2H), 9.22−9.41 (br, 1H), 10.55−10.62 (br, 1H); ^{13}C NMR δ 15.5, 29.1, 42.0, 108.4, 108.5, 110.9, 118.7, 121.3, 123.6, 128.1, 129.5, 130.3, 131.3, 135.8, 136.1, 137.1, 140.9, 148.5, 149.1, 149.8, 185.1; ESI-MS obsd 356.1756, calcd 356.1757 [(M + H)$^+$, M = $C_{23}H_{21}N_3O$]. Anal. Calcd for $C_{23}H_{21}N_3O$: C, 77.72; H, 5.96; N, 11.82. Found: C, 77.88; H, 5.97; N, 11.48.

General Protocol for the Bromination of 1-Acyldipyrromethanes (Method 2). Following a general procedure,[20,21] a solution of 1-acyldipyrromethane (**5a**−**h**, **11b**−**d**, **11h**; 1.00−5.40 mmol, 0.1 M) in dry THF (10.0−54.0 mL) was cooled to −78 °C under argon. A solid sample of NBS (1.00−5.40 mmol) was added to give a concentration of 0.1 M, and the reaction mixture was stirred at −78 °C for 1 h. Hexanes (20.0 mL) and water (20.0 mL) were added, and the reaction mixture was allowed to warm to room temperature. Ethyl acetate was added. The organic phase was washed (water, brine), dried (K_2CO_3), and concentrated under reduced pressure without heating. The crude product was purified by column chromatography [silica, hexanes/ethyl acetate (3:1)] to afford the corresponding 1-acyl-9-bromodipyrromethane.

1-Bromo-9-hexanoyl-5-phenyldipyrromethane (5b-Br). Following Method 2, a solution of **5b** (1.728 g, 5.40 mmol) in THF (54.0 mL) was treated with NBS (0.961 g, 5.40 mmol) to afford a brown paste (1.36 g, 63%): ^{1}H NMR δ 0.87−0.90 (m, 3H), 1.31−1.33 (m, 4H), 1.61−1.65 (m, 2H), 2.52−2.69 (m, 2H), 5.45 (s, 1H), 5.89−5.91 (m, 1H), 6.04−6.07 (m, 2H), 6.82−6.84 (m, 1H), 7.12−7.14 (m, 2H), 7.25−7.30 (m, 3H), 8.52−8.66 (br, 1H), 9.72−9.92 (br, 1H); ^{13}C NMR δ 14.2, 22.7, 25.5, 31.9, 37.9, 44.3, 98.0, 109.9, 110.56, 110.6, 117.7, 127.6, 128.4, 128.9, 131.9, 132.7, 140.2, 140.4, 191.8; FAB-MS obsd 399.1073, calcd 399.1072 [(M + H)$^+$, M = $C_{21}H_{23}BrN_2O$]. Anal. Calcd for $C_{21}H_{23}BrN_2O$: C, 63.16; H, 5.81; N, 7.02. Found: C, 62.94; H, 5.88; N, 6.85.

1-Bromo-9-(pentafluorobenzoyl)-5-phenyldipyrromethane (5c-Br). Following Method 2, a solution of **5c** (0.833, 2.00 mmol) in THF (20.0 mL) was treated with NBS (0.354 g, 2.00 mmol) at −78 °C to afford a brown foam (0.686 g, 69%): mp 85−87 °C; ^{1}H NMR δ 5.49 (s, 1H), 5.86−5.96 (m, 1H), 6.09−6.11 (m, 2H), 6.62−6.72 (m, 1H), 7.16−7.22 (m, 2H), 7.31−7.37 (m, 3H), 8.02−8.22 (br, 1H), 9.68−9.84 (br, 1H); ^{13}C NMR (THF-d_8) δ 45.3, 98.3, 110.3, 110.4, 110.5, 112.0, 112.2, 122.5, 127.8, 128.0, 129.6, 132.6, 134.4, 137.4, 139.9, 141.7, 142.1, 143.7, 144.3, 145.8, 146.2, 171.7; ESI-MS obsd 495.01176, calcd 495.01259 [(M + H)$^+$, M = $C_{22}H_{12}BrF_5N_2O$]. Anal. Calcd for $C_{22}H_{12}BrF_5N_2O$: C, 53.36; H, 2.44; N, 5.66. Found: C, 53.28; H, 2.16; N, 6.02.

General Protocol for the Synthesis of Bilanes (Method 3). Following the published procedure,[12] a solution of a 1-bromo-9-acyldipyrromethane (**5a**−**h-Br**) in dry THF/MeOH (3:1, 0.0125 M) under argon at room temperature was treated with $NaBH_4$ (25.0 mol equiv versus **5a**−**h-Br**) in small portions with rapid stirring. The progress of the reaction was monitored by TLC analysis [silica, hexanes/ethyl acetate (3:1)]. The reaction was complete in ∼30 min. The reaction mixture was poured into a mixture of saturated aqueous NH_4Cl (25 mL) and ethyl ether (25 mL). The organic phase was separated, washed (water, brine), dried (K_2CO_3), and concentrated under reduced pressure at ambient temperature to yield the corresponding dipyrromethane-carbinol (**5a**−**h-Br-OH**) as a yellow-orange paste. The resulting product was transferred to an oven-dried round-bottomed flask with diethyl ether (10.0 mL). The diethyl ether solution of the dipyrromethane-carbinol was concentrated to give an orange paste. For improved stability, the dipyrromethane-carbinol was handled as a paste containing residual diethyl ether rather than as a dry solid. A sample of a 1-acyldipyrromethane **6a**−**h** (1.00 mmol, 0.5 M) was added. A septum was fitted to the flask, and anhydrous acetonitrile was added under a slow argon flow. The resulting reaction mixture was stirred for 1 min, whereupon $Yb(OTf)_3$ (as a 10 mM stock solution in methanol, or as a solid, to give a final acid concentration of 3.3−230 mM) was slowly added. The reaction mixture darkened. The reaction mixture was stirred until all of the dipyrromethane-carbinol was consumed [0.5−5 h; TLC analysis: silica, hexanes/ethyl acetate (3:1)]. An aliquot was removed from the reaction mixture and checked by MALDI-MS (POPOP). No detectable scrambling was observed. The reaction mixture was neutralized by the addition of triethylamine [10 mol equiv versus $Yb(OTf)_3$]. The reaction mixture turned light brown. The resulting mixture was diluted with diethyl ether (∼50 mL), washed (water, brine), dried (K_2CO_3), and concentrated to afford a light-brown foam. The crude product was chromatographed to afford the bilane as a light-brown foam, presumably as a mixture of stereoisomers.

1-Bromo-15-(4-*tert*-butylphenyl)-19-(isonicotinoyl)-10-(4-methylphenyl)-5-phenylbilane (2e). Following Method 3, a solution of **5a-Br** (0.105 g, 0.250 mmol) in dry THF/MeOH (20.0 mL, 3:1) was treated with $NaBH_4$ (0.236 g, 6.25 mmol). The resulting

carbinol **5a-Br-OH** in dry acetonitrile (0.340 mL) was treated with **6e** (0.096 g, 0.25 mmol) and $Yb(OTf)_3$ (0.160 mL of a 10.0 mM stock solution in anhydrous MeOH). The resulting reaction mixture was stirred at room temperature for 4 h. The standard workup and column chromatography [silica, hexanes/ethyl acetate (1:4)] afforded a brown foam (0.119 g, 61%), presumably as a mixture of 8 stereoisomers: mp 92−95 °C; ^{1}H NMR (THF-d_8) δ 1.29 (s, 9H), 2.27 (s, 3H), 5.22−5.25 (m, 1H), 5.27−5.29 (m, 1H), 5.41−5.45 (m, 1H), 5.49−5.56 (m, 5H), 5.85−5.89 (m, 1H), 5.91−5.95 (m, 1H), 6.71−6.74 (m, 1H), 7.01−7.06 (m, 4H), 7.09−7.14 (m, 5H), 7.19−7.21 (m, 2H), 7.29−7.31 (m, 2H), 7.61−7.62 (m, 2H), 8.68 (m, 2H), 9.54−9.61 (br, 1H), 9.66−9.69 (br, 1H), 10.31−10.42 (br, 1H), 11.18−11.26 (br, 1H); ^{13}C NMR (THF-d_8) δ 21.3, 31.9, 35.2, 44.8, 45.0, 45.4, 97.2, 107.7, 107.9, 109.8, 110.1, 111.3, 120.9, 123.2, 125.9, 127.2, 128.9, 129.4, 129.5, 129.53, 131.2, 132.3, 132.4, 132.44, 133.1, 133.2, 134.3, 134.4, 134.5, 134.9, 134.93, 135.0, 136.3, 136.4, 140.5, 141.9, 144.1, 144.2, 145.1, 146.7, 150.2, 151.1, 182.5; MALDI-MS (POPOP) obsd 782.1, 783.1, 784.1, 785.1, 786.1, 787.1, 788.1, 789.1, calcd 785.27292 ($C_{48}H_{44}BrN_5O$); ESI-MS obsd 786.2777, calcd 786.2801 [$(M + H)^+$, M = $C_{48}H_{44}BrN_5O$].

General Protocol for the Synthesis of Porphyrins (Method 4). Following the reported procedure,[12] an oven-dried one-necked round-bottomed flask (10 mL) containing a dry stir bar and fitted with a vented Teflon septum was treated successively with a sample of a bilane (**1b**−**e**, 0.300 mmol) and dry toluene (3.00 mL). DBU (0.450 mL, 3.00 mmol, 10.0 mol equiv versus the bilane) was added dropwise at room temperature. The reaction mixture darkened with stirring over the course of 5 min. A sample of $MgBr_2$ (0.166 g, 0.900 mmol, 3.00 mol equiv versus the bilane) was added in one portion under vigorous stirring. (Note that a dry flask is essential, as is vigorous stirring, so that $MgBr_2$ does not clump as a solid on the bottom of the flask, which typically lowers the yield of porphyrin.) The reaction mixture was stirred for 1 min at room temperature. The flask was fitted with a reflux condenser (4 cm diameter × 30 cm) having the top end open to the atmosphere, and the flask was placed in an oil bath preheated to 115 °C. The reaction mixture (heterogeneous) was stirred at 115 °C. The crude reaction mixture was checked by absorption spectroscopy and TLC analysis (silica CH_2Cl_2). In most cases the formation of porphyrin was complete in 2−3 h. The crude reaction mixture was checked by LD-MS analysis for possible scrambling. The crude reaction mixture was concentrated and then chromatographed [alumina, CH_2Cl_2 → CH_2Cl_2/ethyl acetate (4:1) → (2:1)]. The porphyrin-containing fraction was concentrated to afford a purple solid.

20-(4-*tert*-Butylphenyl)-15-(4-methylphenyl)-10-phenyl-5-(4-pyridyl)porphinatomagnesium(II) (MgP-2e). Application of Method 4 with **2e** (0.059 g, 0.075 mmol), DBU (0.113 mL, 0.750 mmol), and $MgBr_2$ (0.042 g, 0.25 mmol) in toluene (0.750 mL) with chromatographic workup [alumina, CH_2Cl_2 → CH_2Cl_2/ethyl acetate → (3:1) → (2:1) → ethyl acetate/MeOH (30:1)] afforded a solid. The resulting product was washed with hexanes (3 × 5 mL) to afford a purple solid (0.029 g, 54%): ^{1}H NMR δ 1.64 (s, 9H), 2.69 (s, 3H), 7.59 (m, 2H), 7.74−7.76 (m, 3H), 7.83−7.86 (m, 2H), 8.08−8.20 (m, 8H), 8.75−8.80 (m, 2H), 8.83−8.85 (m, 8H); LD-MS obsd 708.2; ESI-MS obsd 707.2893, calcd 707.2901 ($C_{48}H_{37}MgN_5$); λ_{abs} (toluene) 407, 427, 564, 604 nm.

General Protocol for the Synthesis of Porphyrins Bearing Three Pyridyl Substituents (Method 5). The procedure differed from Method 4 in the following ways: (1) Bilane formation was carried out in neat acetonitrile (no methanol). (2) The bilane was not readily purified and hence was used in crude form, whereupon a small amount of unreacted 1-acyldipyrromethane gave the corresponding *trans*-A_2B_2-porphyrin. (3) Porphyrin formation was carried out under microwave irradiation. (4) The magnesium porphyrin was demetalated and the free base porphyrin was isolated.

(i) Bilane formation. A sample of **7-Br** (0.217 g, 0.500 mmol) in dry THF/MeOH (40.0 mL, 3:1) was treated all-at-once with $NaBH_4$ (0.473 g, 12.5 mmol, 25.0 mol equiv) under argon at room temperature. On the basis of TLC analysis of the crude reaction mixture (silica, ethyl acetate) the reaction was complete in ∼30 min. The reaction mixture was poured into a mixture of saturated aqueous NH_4Cl (∼10 mL) and diethyl ether (∼10 mL). The organic phase was separated, washed (water, brine), dried (K_2CO_3), and concentrated until some diethyl ether (∼5 mL) remained. The resulting orange-yellow solution (**7-Br-OH**) was transferred to an oven-dried round-bottomed flask (25 mL). A sample of 1-acyldipyrromethane (0.164 g, 0.500 mmol) was added followed by anhydrous acetonitrile (1 mL) under a slow flow of argon. The resulting solution was concentrated under low pressure with a rotary evaporator (ambient temperature) to largely remove the ethyl ether and give a volume of ∼1 mL (predominantly acetonitrile). The resulting orange-red solution was stirred for 1 min, whereupon $Yb(OTf)_3$ (0.142 g, 0.230 mmol) was added. The reaction mixture immediately turned dark red-orange. An aliquot was removed from the reaction mixture at various times and checked by TLC analysis (silica, ethyl acetate). Up to four components were observed [trace of unreacted 1-acyldipyrromethane, target bilane, unknown streaking red component, and the carbinol (R_f 0.19, 0.39, 0.58, and 0.81, respectively), which upon exposure to bromine were orange, dark brown, dark pink, and dark red, respectively]. The reaction mixture was stirred until all of the carbinol was consumed. MALDI-MS (POPOP) analysis of the crude reaction mixture gave a peak (*m*/*z* 745.9) consistent with the target bilane. The reaction was neutralized by the addition of triethylamine (0.020 mL). The resulting mixture was diluted with ethyl acetate (∼30 mL) and washed with water and brine. The organic layer was dried (K_2CO_3) and concentrated to afford a dark red-brown paste.

(ii) Porphyrin Formation under Microwave Conditions. The crude bilane was transferred to a 10-mL glass tubular reaction vessel containing a magnetic stir bar and toluene (5 mL). The headspace contained air. A sample of DBU (0.750 mL, 5.00 mmol) was added via syringe. The vessel was sealed with a septum. The resulting mixture was stirred for 5 min at room temperature. The reaction mixture darkened. The septum was removed and $MgBr_2$ (0.276 g, 1.50 mmol) was added all-at-once. The vessel was sealed with a septum and the resulting heterogeneous reaction mixture was stirred at room temperature for 1 min. The vessel was subjected to microwave irradiation at 100 W. The protocol was as follows: (1) heat from room temperature to 115 °C (irradiate for 2 min), (2) hold at 115 °C (irradiate for 15 min; the temperature typically overshot to 135 °C and then stabilized after 2 min), (3) allow to cool to room temperature (∼1 min), (4) check the reaction mixture by TLC analysis and absorption spectroscopy, (5) repeat steps 1−3 until porphyrin formation is complete (typically 3−4 h overall). After porphyrin formation was complete, the crude reaction mixture was dissolved in THF (HPLC-grade and stabilizer-free). The solution was concentrated and chromatographed [alumina, THF (HPLC-grade and stabilizer-free) → THF/MeOH (10:1)]. (The use of solvent containing the stabilizer 2,6-di-*tert*-butyl-4-methylphenol resulted in contamination of the porphyrin with the stabilizer following chromatography.) The porphyrin-containing fraction was concentrated. The resulting porphyrin was suspended in methanol (5 mL). The suspension was sonicated for ∼1 min, centrifuged, and decanted to obtain the magnesium porphyrin. In some cases, purification of the crude reaction mixture by alumina column chromatography [alumina, CH_2Cl_2 → THF → THF/MeOH (10:1)] was not successful due to extensive streaking of the magnesium porphyrin. In such cases, the porphyrin-containing fractions were combined, subjected to demetalation, and the product was purified as the free base porphyrin.

(iii) Demetalation. The crude magnesium porphyrin was dissolved in CH_2Cl_2 (5 mL) and demetalated by the addition of TFA (0.030 mL). The reaction mixture was stirred for 1 h, whereupon a sample of triethylamine was added (0.020 mL). The crude reaction mixture was washed (water, brine), dried (Na_2SO_4), and concentrated. The resulting product was chromatographed [silica, CH_2Cl_2

→ CH_2Cl_2/THF (1:10) → THF]. The porphyrin-containing fractions were concentrated and combined to afford the free base porphyrin.

10-(4-Ethylphenyl)-5,15-di-3-pyridyl-20-(2-pyridyl)porphinatomagnesium(II) (MgP-9a). Following Method 5, **7-Br** (0.217 g, 0.500 mmol) and **8a** (0.164 g, 0.500 mmol) gave a red-brown paste. The crude bilane was treated with DBU (0.750 mL, 5.00 mmol) and $MgBr_2$ (0.276 g, 1.50 mmol) in toluene (5 mL) under microwave conditions followed by standard workup to afford a purple solid (39 mg, 12%): ^{1}H NMR (DMSO-d_6) δ 1.44 (t, J = 7.6 Hz, 3H), 2.93 (q, J = 7.6 Hz, 2H), 7.59 (d, J = 7.0 Hz, 2H), 7.76−7.84 (m, 3H), 8.05−8.06 (m, 2H), 8.18−8.19 (m, 1H), 8.24−8.26 (m, 1H), 8.56 (d, J = 7.0 Hz, 2H), 8.68−8.72 (m, 6H), 8.78 (d, J = 4.6 Hz, 2H), 8.96 (d, J = 4.6 Hz, 2H), 9.01 (d, J = 4.6 Hz, 1H), 9.28−9.36 (m, 2H); LD-MS obsd 667.4; ESI-MS obsd 667.2339, calcd 667.2335 [(M + H)$^+$, M = $C_{43}H_{29}MgN_7$]; λ_{abs} (THF) 409, 430, 571, 612 nm.

General Protocol for the Synthesis of Bilanes and Porphyrins Bearing Alkyl Substituents (Method 6). The procedure differs from Method 4 in the following ways: (1) The 1-acyldipyrromethane (typically a paste) was handled as a solution in acetonitrile. (2) Bilane formation was carried out in neat acetonitrile (no methanol) and at 50 mM instead of 500 mM. (3) Porphyrin formation was carried out under microwave irradiation. (4) The magnesium porphyrin was demetalated and the free base porphyrin was isolated.

(i) Bilane Formation. A sample of 9-bromo-1-acyldipyrromethane **11-Br** (0.250 mmol) in dry THF/MeOH (20.0 mL, 3:1) was treated with $NaBH_4$ (0.236 g, 6.25 mmol, 25.0 mol equiv versus **11-Br**) to give the carbinol. On the basis of TLC analysis of the crude reaction mixture [silica, hexanes/ethyl acetate (3:1)] the reaction was complete in ∼30 min. The reaction mixture was poured into a mixture of saturated aqueous NH_4Cl in diethyl ether (∼40 mL). The organic phase was extracted with diethyl ether, washed (water, brine), dried (K_2CO_3) and transferred to a round-bottomed flask. A solution of 1-acyldipyrromethane **11** in acetonitrile (5 mL) was transferred to the resulting carbinol solution via syringe. (Note that alkyl-substituted 1-acyldipyrromethanes typically exist as a paste at room temperature; therefore, the 1-acyldipyrromethane was weighed in a vial and transferred as a solution). The resulting solution was concentrated under low pressure with a rotary evaporator (ambient temperature) to largely remove the ethyl ether and give a volume of ∼5 mL (predominantly acetonitrile). The resulting orange-red solution (containing a residual amount of ethyl ether) was treated with Yb(OTf)$_3$ (10.0 mg, 0.0165 mmol, ∼3.3 mM) under a slow flow of argon. An aliquot was removed from the reaction mixture after 30 min and checked by TLC analysis [silica, hexanes/ethyl acetate (3:1)]. A trace amount of unreacted **11** and bilane **12** were observed. Exposure of the TLC plate to bromine further identified the components by the characteristic orange spot and dark brown spot, respectively. The reaction was neutralized with triethylamine [0.0250 mL, 0.165 mmol, 10 mol equiv versus Yb(OTf)$_3$]. The resulting mixture was diluted with ethyl acetate (∼30 mL) and washed with water and brine. The organic layer was dried (K_2CO_3) and concentrated to afford a dark brown paste. The resulting crude product was chromatographed [silica, hexanes/ethyl acetate (3:1)] to afford a brown paste.

(ii) Porphyrin Formation under Microwave Conditions. A sample of bilane **12** (0.10 mmol) was transferred to a 10 mL glass reaction vessel containing a magnetic stir bar and toluene (1 mL). The headspace contained air. A sample of DBU (0.15 mL, 1.0 mmol) was added via syringe. The vessel was sealed with a septum. The resulting mixture was stirred for 5 min at room temperature. The reaction mixture darkened. The septum was removed, and $MgBr_2$ (0.055 g, 0.30 mmol) was added. The vessel was sealed with a septum, and the resulting heterogeneous reaction mixture was stirred at room temperature for 1 min. The vessel was subjected to microwave irradiation at 100 W. The protocol was as follows: (1) heat from room temperature to 115 °C (irradiate for 2 min), (2) hold at 115 °C (irradiate for 30 min; temperature typically overshot to 135 °C and then stabilized after 2 min), (3) allow to cool to room temperature (∼1 min), (4) check the reaction mixture by TLC analysis [silica, CH_2Cl_2, a streaking red-brown unidentified product and a magnesium porphyrin typically were observed] and absorption spectroscopy (3 bands were observed at 303, 425, and 525 nm), (5) repeat steps 1−4 until the intermediate was largely consumed. Most reactions were quite sluggish, in which case the reaction flask was treated with microwave irradiation for a longer period of time (∼6 h) prior to analysis. The total overall microwave irradiation time typically was ∼24 h. The crude reaction mixture was transferred to a round-bottomed flask with THF (HPLC-grade and lacking stabilizer) and concentrated. The crude product was washed (water, brine), dried (Na_2SO_4), and concentrated.

(iii) Demetalation. The procedure was identical to Method 5.

1-Bromo-15-butyl-5-ethyl-19-hexanoyl-10-propylbilane (12f). Following Method 6, a solution of **11c-Br** (0.242 g, 0.750 mmol) in dry THF/MeOH (60.0 mL, 3:1) was treated with $NaBH_4$ (0.708 g, 18.8 mmol). The standard workup procedure was followed. A solution of **11g** (0.225 g, 0.750 mmol) in acetonitrile (15.0 mL) was added to the carbinol solution in ethyl ether (∼45.0 mL). The ether was removed under reduced presssure, and Yb(OTf)$_3$ (31.0 mg, 0.0495 mmol, 3.30 mM) was added. The reaction mixture was stirred for 30 min at room temperature. The standard workup and column chromatography afforded a brown paste (0.370 g, 81%), presumably as a mixture of 8 stereoisomers: ^{1}H NMR (THF-d_8) δ 0.81−0.92 (m, 12H), 1.28−1.34 (m, 8H), 1.59−1.66 (m, 4H), 1.83−1.93 (m, 6H), 2.64 (t, J = 7.2 Hz, 2H), 3.67 (t, J = 7.6 Hz, 1H), 3.79 (t, J = 7.6 Hz, 1H), 3.89 (t, J = 7.8 Hz, 1H), 5.67−5.69 (m, 3H), 5.73−5.74 (m, 2H), 5.85−5.87 (m, 2H), 6.72−6.75 (m, 1H), 9.01−9.08 (br, 1H), 9.16−9.24 (m, 1H), 10.04−10.16 (br, 1H), 10.42−10.54 (br, 1H); ^{13}C NMR (THF-d_8) δ 22.6, 24.2, 24.3, 31.5, 33.3, 33.4, 38.9, 40.8, 42.5, 45.7, 45.72, 47.9, 48.2, 48.3, 48.6, 49.0, 50.8, 105.9, 115.1, 115.3, 117.2, 117.6, 119.8, 126.5, 141.9, 142.4, 142.5, 143.1, 143.8, 143.9, 144.1, 144.2, 146.9, 153.6; ESI-MS obsd 606.29350, calcd 606.29333 ($C_{34}H_{47}BrN_4O$).

5-Butyl-15-ethyl-10-pentyl-20-propylporphyrin (P-12f). Application of Method 6 with **12f** (0.122 g, 0.200 mmol), DBU (0.300 mL, 2.00 mmol), and $MgBr_2$ (0.111 g, 0.600 mmol) in toluene (2.0 mL) afforded a crude product. Demetalation of the crude product was followed by chromatographic workup [silica, hexanes/CH_2Cl_2 (1:1)] to afford a purple solid (0.025 g, 24%): ^{1}H NMR δ −2.68 (s, 2H), 0.98 (t, J = 7.4 Hz, 3H), 1.13 (t, J = 7.4 Hz, 3H), 1.32 (t, J = 7.4 Hz, 3H), 1.51−1.57 (m, 2H), 1.76−1.84 (m, 4H), 2.11 (t, J = 7.4 Hz, 3H), 2.48−2.56 (m, 6H), 4.87−4.99 (m, 8H), 9.45−9.46 (m, 8H); ^{13}C NMR δ 14.4, 14.6, 15.2, 22.9, 23.0, 23.9, 29.0, 31.8, 32.9, 35.5, 35.7, 37.6, 38.6, 41.0, 118.3, 118.6, 118.7, 119.9, 127.2−129.3 (br); MALDI-FT-ICR-MS obsd 507.35271, calcd 507.34877 [(M + H)$^+$, M = $C_{34}H_{42}N_4$]; λ_{abs} (toluene) 419, 521, 554, 602, 662 nm.

Porphyrin Formation via a Bilene: 20-(4-*tert*-Butylphenyl)-5-(4-ethylphenyl)-10-phenylporphinatomagnesium(II) (MgP-2i). Bilene formation was accomplished with catalysis either by (i) Yb(OTf)$_3$ or (ii) *p*-toluenesulfonic acid followed by (iii) porphyrin formation. (i) Yb(OTf)$_3$ catalysis: A solution of **5h-Br** (0.105 g, 0.250 mmol) in acetonitrile (2.35 mL) was treated with Yb(OTf)$_3$ (1.15 mL, 0.0115 mmol, from a 10.0 mM stock solution in CH_3CN/MeOH (3:1)). The reaction mixture was stirred for 5 min and **6a** (0.106 g, 0.250 mmol) was added. The resulting heterogeneous mixture was stirred at room temperature for 30 min. No product was observed. A sample of Yb(OTf)$_3$ (0.0420 g, 0.0682 mmol, total acid concentration 23.0 mM) was added. The resulting heterogeneous mixture was stirred at room temperature for 2 h. On the basis of TLC analysis [silica, hexanes/ethyl acetate (3:1)] only a trace amount of product was observed. The reaction mixture was placed in an oil bath preheated to 55 °C. The reaction mixture became homogeneous in 10 min, and was maintained at 55 °C for 2 h. The TLC analysis revealed the presence of a streaking component and a trace amount of unreacted **6a**. The reaction mixture was concentrated. The resulting crude product was washed (water,

brine), dried (Na_2SO_4), and concentrated to give the crude bilene-*b*. (ii) *p*-Toluenesulfonic acid catalysis: A solution of **5h-Br** (0.052 g, 0.13 mmol) in CH_2Cl_2 (0.600 mL) was treated with *p*-toluenesulfonic acid monohydrate solution [0.0285 g, 0.150 mmol in CH_2Cl_2/MeOH (0.625 mL, 24:1)]. The reaction mixture was stirred for 5 min and **6a** (0.051 g, 0.13 mmol) was added. The resulting heterogeneous mixture was stirred at room temperature for 30 min. TLC analysis (silica, CH_2Cl_2) revealed the presence of a streaking component. A sample of triethylamine (0.020 mL) was added. The resulting crude product was washed (water, brine), dried (Na_2SO_4), and concentrated to give the crude bilene-*b*. (iii) The crude bilene-*b* (here reported from $Yb(OTf)_3$ catalysis) was dissolved in toluene (2.5 mL) and treated with DBU (0.375 mL, 2.50 mmol) and $MgBr_2$ (0.138 g, 0.750 mmol) at 115 °C with exposure to air for ~4−6 h. Column chromatography [silica, CH_2Cl_2 → CH_2Cl_2/ethyl acetate (4:1) → (2:1)] afforded 5,15-bis(4-*tert*-butylphenyl)-10,20-bis(4-ethylphenyl)porphinatomagnesium(II) (<2% yield on the basis of absorption spectroscopy with an assumed molar absorption coefficient at the Soret band of 500 000 $M^{-1}cm^{-1}$) followed by the title compound. Fractions containing the latter were concentrated to give a purple solid (0.016 g, 11%): ^{1}H NMR δ 1.54 (t, J = 7.6 Hz, 3H), 1.63 (s, 9H), 2.99 (q, J = 7.6 Hz, 2H), 7.54 (d, J = 7.6 Hz, 2H), 7.74−7.76 (m, 5H), 8.10−8.16 (m, 4H), 8.22−8.23 (m, 2H), 8.89−8.95 (m, 4H), 8.98−9.04 (m, 2H), 9.29 (s, 2H), 10.12 (s, 1H); ^{13}C NMR δ 15.9, 29.0, 32.0, 35.1, 106.3, 121.0, 121.5, 122.3, 123.5, 125.9, 126.5, 127.2, 131.6, 131.7, 132.1, 132.2, 132.5, 132.8, 134.8, 134.82, 134.9, 135.0, 140.8, 141.3, 143.1, 143.9, 149.8, 149.9, 150.0, 150.2; LD-MS obsd 644.5, ESI-MS obsd 644.2784, calcd 644.2792 ($C_{44}H_{36}MgN_4$); λ_{abs} (toluene) 422, 558, 597 nm. When the porphyrin-forming reaction was carried out for 15 h, the product was the singly fused porphyrin dimer, which was isolated following column chromatography [silica, CH_2Cl_2 → CH_2Cl_2/ethyl acetate (4:1) → (2:1)] as a purple solid (0.013 g, 8%). Data for the singly fused porphyrin dimer of unknown stereochemical configuration (**MgP-2i-dimer**): ^{1}H NMR δ 1.52−1.59 (m, 24H), 3.05 (q, J = 9.6 Hz, 4H), 7.59−7.63 (m, 16H), 7.94−8.21 (m, 4H), 8.12−8.15 (m, 4H), 8.21−8.23 (m, 6H), 8.52−8.59 (m, 4H), 8.88−8.97 (m, 8H); ^{13}C NMR δ 15.9, 29.1, 31.9, 35.0, 121.2, 122.2, 122.5, 122.7, 123.3, 126.0, 126.4, 127.1, 131.5, 131.6, 131.8, 131.9, 132.1, 132.2, 134.2, 134.6, 134.9, 135.0, 140.8, 141.3, 143.2, 144.0, 149.6, 149.8, 149.9, 150.1, 150.2, 150.4, 150.7, 155.2, 155.3; LD-MS obsd 1286.9, FAB-MS obsd 1286.5554, calcd 1286.5424 ($C_{88}H_{70}Mg_2N_8$); λ_{abs} (toluene) 427 (br), 465 (br), 577 (br), 620 nm.

Acknowledgment. This work was funded by the NIH (GM36238). Mass spectra were obtained at the Mass Spectrometry Laboratory for Biotechnology at North Carolina State University. Partial funding for the facility was obtained from the North Carolina Biotechnology Center and National Science Foundation.

Supporting Information Available: Stability information about bilanes; procedures for preparing compounds; Experimental Section; and spectral data for selected compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

JO8010396