JOC Article

9-Acylation of 1-Acyldipyrromethanes Containing a Dialkylboron Mask for the α-Acylpyrrole Motif

Syeda Huma H. Zaidi, Kannan Muthukumaran, Shun-ichi Tamaru, and Jonathan S. Lindsey*

Department of Chemistry, North Carolina State University, Raleigh, North Carolina 27695-8204

jlindsey@ncsu.edu

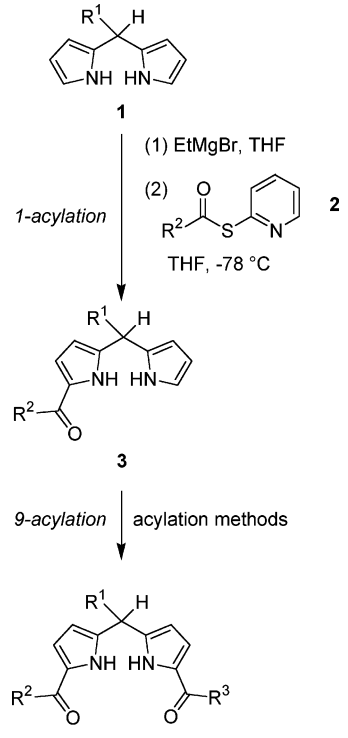
Received August 12, 2004

1,9-Diacyldipyrromethanes are important precursors to porphyrins, yet synthetic access remains limited owing to (1) poor conversion in the 9-acylation of 1-acyldipyrromethanes and (2) handling difficulties because acyldipyrromethanes typically streak upon chromatography and give amorphous powders upon attempted crystallization. A reliable means for converting a dipyrromethane to a 1-acyldipyrromethane−dialkylboron complex was recently developed, where the dialkylboron (BR_2) unit renders the complex hydrophobic and thereby facilitates isolation. Herein a refined preparation of 1,9-diacyldipyrromethanes is presented that employs the 1-acyldipyrromethane−BR_2 complex as a substrate for 9-acylation. The dialkylboron unit provides protection for the α-acylpyrrole unit. 9-Acylation requires formation of the pyrrolyl−MgBr reagent and the presence of 1 equiv of a nonnucleophilic base to quench the proton liberated upon α-acylation. Reaction of the 1-acyldipyrromethane−BR_2 complex (1 equiv) with mesitylmagnesium bromide (2 equiv) followed by the addition of an acylating agent (*S*-2-pyridyl thioate or acid chloride, 1.1 equiv) gives the corresponding 1,9-diacyldipyrromethane−BR_2 complex. The acylation method afforded 1,9-diacyldipyrromethane−BR_2 complexes with limited or no chromatography in yields of 64−92%. The 1,9-diacyldipyrromethane−BR_2 complexes are stable to routine handling, are readily soluble in common organic solvents, crystallize readily, and can now be prepared in multigram quantities through use of stoichiometric quantities of reagents.

Introduction

The acylation of dipyrromethanes to form 1,9-diacyldipyrromethanes is an essential step in the rational synthesis of porphyrins.[1] Dipyrromethanes with identical acyl groups at the 1- and 9-positions are key precursors to A_3B-, *trans*-A_2B_2-, and *trans*-AB_2C-porphyrins. Dipyrromethanes bearing two different acyl groups at the 1- and 9-positions are required precursors to *cis*-A_2B_2-, *cis*-A_2BC-, and ABCD-porphyrins. The successive acylations are accomplished as follows: Treatment of a dipyrromethane (**1**) with EtMgBr (to form the pyrrolyl Grignard reagent[2]) followed by an *S*-2-pyridyl thioate (**2**) affords the 1-acyldipyrromethane (**3**) in high yield (Scheme 1).[3] Reaction of a 1-acyldipyrromethane (**3**) with EtMgBr and an acid chloride affords the 1,9-diacyldipyrromethane (**4**).[1] Other methods that do not proceed via the pyrrolyl Grignard reagent (Friedel−Crafts, Vilsmeier, benzoxathiolium salt) also have been examined for the 9-acylation of a 1-acyldipyrromethane.[4] Regardless of synthetic method, purification has been difficult because acyldipyrromethanes (**3**, **4**) typically streak extensively upon chromatography and give amorphous powders upon attempted crystallization.

SCHEME 1

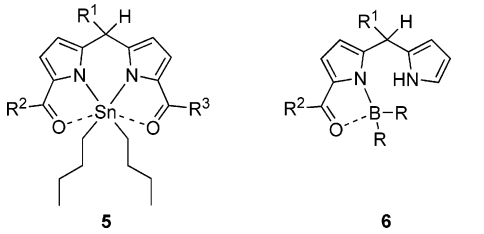


Recently we have developed two complexation aids to facilitate handling of acyldipyrromethanes. The reaction

(1) Rao, P. D.; Dhanalekshmi, S.; Littler, B. J.; Lindsey, J. S. *J. Org. Chem.* **2000**, *65*, 7323−7344.
(2) Anderson, H. J.; Loader, C. E. In *Pyrroles*; Jones, R. A., Ed.; John Wiley & Sons: New York, 1990; Part I, pp 397−497.
(3) Rao, P. D.; Littler, B. J.; Geier, G. R., III; Lindsey, J. S. *J. Org. Chem.* **2000**, *65*, 1084−1092.
(4) Tamaru, S.-I.; Yu, L.; Youngblood, W. J.; Muthukumaran, K.; Taniguchi, M.; Lindsey, J. S. *J. Org. Chem.* **2004**, *69*, 765−777.

10.1021/jo048587d CCC: $27.50 © 2004 American Chemical Society
Published on Web 11/04/2004

CHART 1



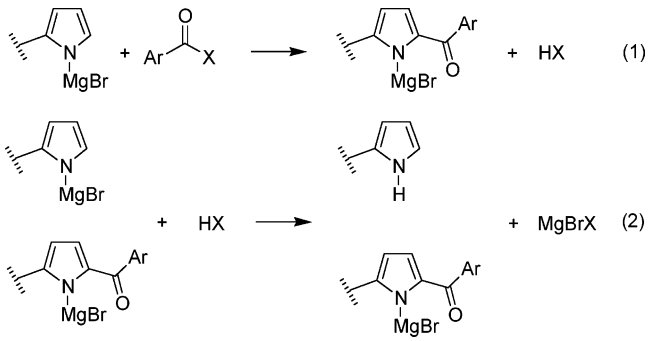
5 **6**

of a 1,9-diacyldipyrromethane with Bu_2SnCl_2 gives the corresponding dibutyl(5,10-dihydrodipyrrinato)tin(IV) complex (**5**), which can be chromatographed without streaking (Chart 1).[4] The reaction is selective for dipyrromethanes that bear acyl groups at both the 1- and 9-positions. The reaction of a 1-acyldipyrromethane with a dialkylboron triflate (R_2B-OTf) gives the corresponding 1-acyldipyrromethane$-BR_2$ complex (**6**).[5] Suitable dialkylboron species include dibutylboron and 9-BBN entities, but the latter are preferable owing to the facile crystallization of the 9-BBN complexes. Both **5** and **6** are more hydrophobic than the corresponding acyldipyrromethanes because each α-acylpyrrole motif is coordinated to the tin or boron atom, thereby ensheathing this polar entity. Both complexation methods have been employed for the purification of the acyldipyrromethanes from the crude acylation reaction mixture with limited or no chromatography.

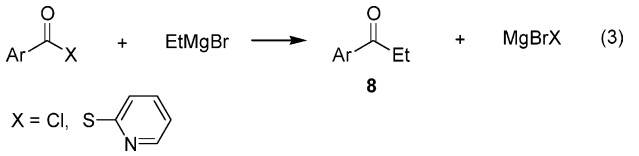
While the 1-acylation of dipyrromethanes proceeds well, the 9-acylation has proved more problematic and generally affords yields of ~60%. The difficulty with 9-acylation via the pyrrolyl Grignard reagent has led to use of a more potent acylating agent (e.g., an acid chloride) than the *S*-2-pyridyl thioate (Mukaiyama reagent)[6] employed for the 1-acylation. Although the tin-complexation procedure enables isolation of the 1,9-diacyldipyrromethane, there remains a need to identify approaches for 9-acylation that afford increased yields under milder conditions.

Consideration of the reaction stoichiometry is essential for understanding how to improve the 9-acylation process. The α-acylation of the pyrrolyl Grignard reagent[2] results in liberation of the α-proton (eq 1). The liberated proton will displace the strongest base, which in this case is the pyrrolyl Grignard reagent rather than the Grignard reagent of the α-acylpyrrole product (eq 2). (Note that the pK_a values of pyrrole and α-formylpyrrole are estimated to be 17.5[7] and 15,[8] respectively.) Accordingly, the α-acylation is expected to progress only 50% to completion unless a base is provided to consume the liberated proton. In many cases, an excess of the pyrrolyl Grignard reagent is employed to provide the required base; such an approach may be satisfactory when the acyl species is the more valuable of the two reactants.

For the 9-acylation of a 1-acyldipyrromethane, 2 equiv of EtMgBr are required to remove the two pyrrolic NH protons. In practice, we have employed a third equivalent



of EtMgBr to serve as the base for the α-proton liberated upon acylation. A general problem with this approach stems from reaction of EtMgBr directly with the acylating agent, thereby affording the ketone **8** (eq 3). In this approach, excess quantities of each reagent (e.g., 6 equiv of EtMgBr and 3 equiv of acid chloride, or repetitive addition of EtMgBr and acid chloride) have often been applied with little improvement over the 50% acylation expected if no attempt is made to neutralize the liberated proton.[1] Attempts to use bases to supplement the quantity of EtMgBr required for forming the initial pyrrolyl Grignard reagent have generally afforded little improvement in the yield of the 1,9-diacyldipyrromethane.[4]



In this paper, we describe our studies on the use of 1-acyldipyrromethane$-BR_2$ complexes as acylation substrates. The dialkylboron complex masks the α-acylpyrrolic unit thereby affording only a single pyrrolic site for reaction. In so doing the 9-acylation can be achieved with a Mukaiyama reagent or an acid chloride. We also describe use of the 1,9-diacyldipyrromethane$-BR_2$ complexes in porphyrin-forming reactions following similar procedures employed with 1,9-diacyldipyrromethanes.

Results and Discussion

Investigation of the 9-Acylation of 1-Acyldipyrromethane$-BR_2$ Complexes: Approach. The 1-acyldipyrromethane$-BR_2$ complex **6** requires 1 equiv of EtMgBr to form the pyrrolyl$-$MgBr species (unlike the 2 equiv required for the uncomplexed 1-acyldipyrromethane **3**). Two approaches have been explored to neutralize the proton liberated upon α-acylation. (i) One equivalent of a nonnucleophilic base is included in the reaction medium. (ii) A second equivalent of a hindered Grignard reagent is included. We chose the reaction of 10-(9-borabicyclo[3.3.1]non-9-yl)-5-phenyl-1-*p*-toluoyldipyrromethane (**6a**) as a model system for exploration of these two approaches. The generic method entailed treatment of a solution of **6a** (0.10 mmol) in THF (0.1 mL) at room temperature with a Grignard reagent (1 M solution in THF) followed by the acylating agent (**2a**) (Scheme 2). TLC and ^{1}H NMR analysis indicated the presence of the desired 1,9-diacyldipyrromethane$-BR_2$ complex **7a** and the starting 1-acyldipyrromethane$-BR_2$ complex **6a**. The

(5) Muthukumaran, K.; Ptaszek, M.; Noll, B.; Scheidt, W. R.; Lindsey, J. S. *J. Org. Chem.* **2004**, *69*, 5354−5364.
(6) Araki, M.; Sakata, S.; Takei, H.; Mukaiyama, T. *Bull. Chem. Soc. Jpn.* **1974**, *47*, 1777−1780.
(7) Yagil, G. *Tetrahedron* **1967**, *23*, 2855−2861.
(8) Limage, M.-H.; Lautié, A.; Novak, A. *C. R. Seances Acad. Sci., Ser. B* **1975**, *280*, 601−603.

SCHEME 2

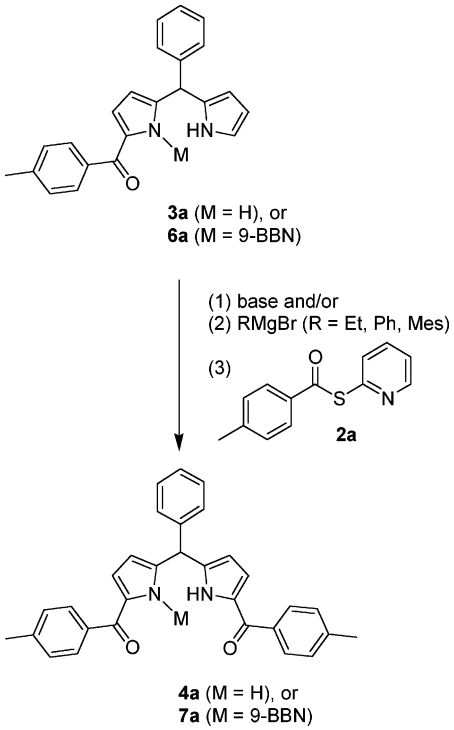
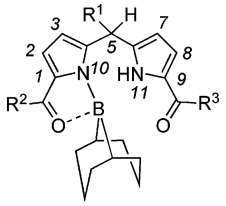


CHART 2



7

relative yield was estimated by ^{1}H NMR spectroscopic analysis of the crude reaction sample by comparing the peak intensity for the H^3 proton signal at ~6.46 or ~6.41 ppm for the 1,9-diacyl- or 1-acyldipyrromethane−BR_2 complex, respectively (or the H^5 proton signal of the uncomplexed species) (Chart 2).

Acylation Studies. We first examined the reaction of **6a** using 2 mol equiv of EtMgBr and 1 equiv of the conjugate acid (BH) of the desired base. The resulting mixture was treated with the Mukaiyama reagent **2a**. In this approach, the reaction of the added EtMgBr with the conjugate acid (BH) of the base forms B−MgBr, the Grignard derivative of the base. The latter must be sufficiently strong to maintain the presence of the pyrrolyl−MgBr upon formation of acidic products. Thus the requirement for the base strength is as follows: Et−MgBr > B−MgBr > pyrrolyl−MgBr > products (α-acylpyrrolyl−MgBr, pyridylthiolate−MgBr). In other words the conjugate acid of the base should have a pK_a greater than that of pyrrole (~17.5) and less than that of ethane (~50). Among nonnucleophilic bases, we examined 2,2,6,6-tetramethylpiperidine (TMP), dicyclohexylamine, and 1,1,1,3,3,3-hexamethyldisilazane (HMDS), which have pK_a values[9] of 37, 36, and 26, respectively. Note that the Grignard derivative of HMDS is known to exist in a multimeric complex.[10]

TABLE 1. Effects of Added Base on the 9-Acylation of 1-Acyldipyrromethanes[a]

entry	**6a** (mmol)	base (mmol)	EtMgBr[b] (mmol)	**2a** (mmol)[c]	product: substrate[d]
1	0.10	−	0.20	0.11	2.7:1.0
2	0.10	TMP(0.10)	0.20	0.10	2.1:1.0
3	0.10	dicyclohexyl-amine (0.10)	0.20	0.10	2.3:1.0
4	0.10	HMDS (0.10)	0.20	0.10	4.0:1.0
5	0.10[e]	HMDS (0.10)	0.20	0.10	4.0:1.0
6	0.10	Li−HMDS (0.10)	0.10	0.11	3.6:1.0
7	0.10	NaH (0.10)	0.10	0.11	1.0:1.0

[a] Reactions were performed with a 1 M solution of 10-(9-borabicyclo[3.3.1]non-9-yl)-5-phenyl-1-*p*-toluoyldipyrromethane (**6a**) in THF at room temperature under argon. [b] EtMgBr was added as a 1.0 M solution in THF. [c] *S*-2-Pyridyl 4-methylbenzothioate (**2a**) was added as a 1 M solution in THF. [d] The ratio was determined by ^{1}H NMR spectroscopic analysis of crude reaction samples. [e] The reaction was performed with a 0.25 M solution of **6a** in THF.

TABLE 2. Effects of Grignard Reagents in the 9-Acylation of 1-Acyldipyrromethanes[a]

entry	**6a** (mmol)	Grignard reagent[b] (mmol)	**2a** (mmol)[c]	product: substrate[d]
1	0.10	EtMgBr (0.20)	0.11	2.7:1.0
2	0.10	PhMgBr (0.20)	0.11	4.4:1.0
3	0.10	MesMgBr (0.20)	0.11	8.7:1.0
4	0.10	*t*-BuMgCl (0.20)	0.11	0.1:1.0
5	0.10	MesMgBr (0.20+0.05)	0.11 + 0.05	>10.0:1.0
6	0.10	MesMgBr (0.30)	0.11	5.0:1.0

[a] Reactions were performed with a 1 M solution of 10-(9-borabicyclo[3.3.1]non-9-yl)-5-phenyl-1-*p*-toluoyldipyrromethane (**6a**) in THF at room temperature under argon. [b] The Grignard reagent was added as a 1.0 M solution in THF. [c] *S*-2-Pyridyl 4-methylbenzothioate (**2a**) was added as a 1 M solution in THF. [d] The ratio was determined by ^{1}H NMR spectroscopic analysis of crude reaction samples.

As a benchmark, the reaction with no added BH species afforded the 1,9-diacyldipyrromethane−BR_2 complex and the unreacted starting material in 2.7:1.0 ratio (entry 1, Table 1). Relatively little improvement was obtained with use of 2,2,6,6-tetramethylpiperidine or dicyclohexylamine (entries 2 and 3), but a significant improvement was obtained with HMDS (4:1, entry 4). Dilution of the reaction mixtures from 1.0 to 0.25 M had little effect on the product distribution (entry 5). The use of tetraphenyldimethyldisilazane in place of HMDS gave comparable acylation results. The use of lithium hexamethyldisilazane (1 equiv) and only 1 equiv of EtMgBr (rather than 2 equiv) also gave comparable results (entry 6). By contrast, use of a nonhindered base (NaH, entry 7) gave quite poor results.

We next examined variation of the composition of the Grignard reagent (2 mol equiv) without an added base. The benchmark experiment with 1 mol equiv of **6a**, 2 mol equiv of EtMgBr, no added base, and 1.1 mol equiv of **2a** is shown in entry 1 (Table 2). A dramatic effect of Grignard reagent was observed in the series MesMgBr (8.7:1) > PhMgBr > EtMgBr > *t*-BuMgCl (~0.1:1.0) (entries 2−4). Addition of MesMgBr and the Mukaiyama reagent in two batches afforded almost complete 9-acyl-

(9) Fraser, R. R.; Mansour, T. S. *J. Org. Chem.* **1984**, *49*, 3442−3443.

(10) Yang, K.-C.; Chang, C.-C.; Huang, J.-Y.; Lin, C.-C.; Lee, G.-H.; Wang, Y.; Chiang, M. Y. *J. Organomet. Chem.* **2002**, *648*, 176−187.

TABLE 3. Essential Features for the 9-Acylation of 1-Acyldipyrromethanes

entry	substrate, mmol[a]	Grignard reagent[b] (mmol)	RCOX (mmol)[c]	product: substrate[d]
1	**6a**, 0.10	EtMgBr (0.20)	**2a** (0.11)	2.7:1.0
2	**6a**, 0.10	EtMgBr (0.20)	ArCOCl (0.11)[e]	2.0:1.0
3	**6a**, 0.10	MesMgBr (0.20)	**2a** (0.11)	8.7:1.0
4	**6a**, 0.10	MesMgBr (0.20)	ArCOCl (0.11)[e]	8.0:1.0
5	**3a**, 0.10	EtMgBr (0.20)	**2a** (0.11)	0.3:1.0
6	**3a**, 0.10	MesMgBr (0.20)	**2a** (0.11)	0.4:1.0
7	**3a**, 0.10	MesMgBr (0.30)	**2a** (0.11)	0.8:1.0

[a] Reactions were performed with a 1 M solution of 10-(9-borabicyclo[3.3.1]non-9-yl)-5-phenyl-1-*p*-toluoyldipyrromethane (**6a**) or 5-phenyl-1-*p*-toluoyldipyrromethane (**3a**) in THF at room temperature under argon. [b] The Grignard reagent was added as a 1.0 M solution in THF. [c] The acylating agent was added as a 1 M solution in THF. [d] The ratio was determined by ^{1}H NMR spectroscopic analysis of crude reaction samples. [e] *p*-Toluoyl chloride.

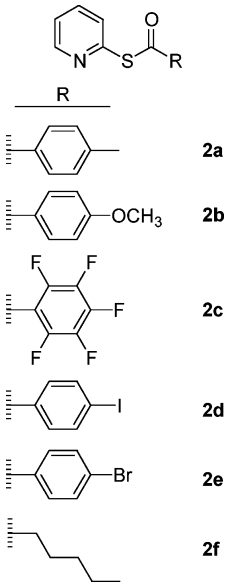
ation and no detectable 1-acyldipyrromethane−BR_2 complex (>10:1 ratio; entry 5). On the other hand, use of excess MesMgBr gave a less efficient acylation (entry 6). Thus, 2 equiv of MesMgBr provides for effective acylation, consistent with the notion that the second equivalent serves as the buffering agent that quenches the proton liberated upon α-acylation.

One experiment was performed to examine the order of addition of reactants. Addition of MesMgBr to the solution containing the 1-acyldipyrromethane−BR_2 complex and the Mukaiyama reagent gave ∼1:1 ratio of diacyl:monoacyl dipyrromethane components. This experiment implies that MesMgBr is not wholly inert toward the Mukaiyama reagent (giving the ketone), and the pyrrolyl−MgBr species should be formed prior to adding the Mukaiyama reagent. Note that MesMgBr is expected to be largely monomeric in THF at the concentrations (0.5−1.0 M) employed in the 9-acylation.[11]

The success of the 9-acylation achieved with the use of the 1-acyldipyrromethane−BR_2 complex (**6a**), 2 mol equiv of MesMgBr, and the Mukaiyama reagent (**2a**) prompted a series of control experiments to establish whether each component was needed. The reaction of **6a**, EtMgBr (2 mol equiv), and the Mukaiyama reagent **2a** afforded a 2.7:1 ratio of 1,9-diacyl- to 1-acyldipyrromethane products (entry 1, Table 3). Replacing the Mukaiyama reagent with *p*-toluoyl chloride resulted in a lower ratio (entry 2). With MesMgBr, the analogous comparison of the Mukaiyama reagent versus *p*-toluoyl chloride gave only a slight change in product ratio, indicating the *p*-toluoyl chloride is as effective for acylation as the Mukaiyama reagent (entries 3 and 4). To check on the necessity of the dialkylboron complex, several acylations were performed with the uncomplexed 1-acyldipyrromethane **3a** and the Mukaiyama reagent **2a**. Regardless of the choice of Grignard reagent (MesMgBr or EtMgBr), very little diacyldipyrromethane was formed (entries 5 and 6). The use of 3 mol equiv of MesMgBr (as required on the basis of stoichiometry considering the two NH protons and the α-proton liberated upon acylation) gave only a slight improvement in the product ratio.

In summary, 9-acylation is most effectively achieved with use of the dialkylboron complex of the 1-acyldipyrromethane and 2 mol equiv of a hindered Grignard reagent. (Use of a nonhindered Grignard reagent and a hindered base affords lower yields of acylation.) The acylation can be achieved with an acid chloride or a Mukaiyama reagent. The success of this method prompted us to reinvestigate the acylation of a dipyrromethane using MesMgBr rather than EtMgBr. No significant improvement was achieved (see Supporting Information).

CHART 3



Scope of Application. The generality of the 9-acylation reactions was examined with 1-acyldipyrromethane−BR_2 complexes bearing different substituents at the 1- and 5-positions. The known Mukaiyama reagents **2a**−**d**,[1] **2e**,[1,3] and **2f**[13] (Chart 3) were prepared as described in the literature or by a slight modification of the original method[6] (Supporting Information). The reaction of a 1-acyldipyrromethane−BR_2 complex (**6a**−**e**) was carried out at the 2-mmol scale with MesMgBr followed by addition of a Mukaiyama reagent (**2a**−**f**) (Scheme 3). The corresponding 1,9-diacyldipyrromethane−BR_2 complexes were obtained in yields of 71−90%. In most cases, the 1,9-diacyldipyrromethane−BR_2 complex was obtained simply by washing the crude solid product with a minimum amount of Et_2O followed by hexanes. In instances where the 1,9-diacyldipyrromethane−BR_2 complex was not obtained in pure form, a subsequent wash of the isolated solid with CH_2Cl_2/hexanes typically removed residual traces of any 1-acyldipyrromethane−BR_2 complex, 1-acyldipyrromethane, or 1,9-diacyldipyrromethane species (see Characterization section below for further discussion). On scale-up the reaction of **6a** (40 mmol) with **2b** gave **7b** in excellent yield (91%, 21.6 g) and purity, though the product contained a trace (<2%) of decomplexed product as estimated by TLC and ^{1}H NMR spectroscopy.

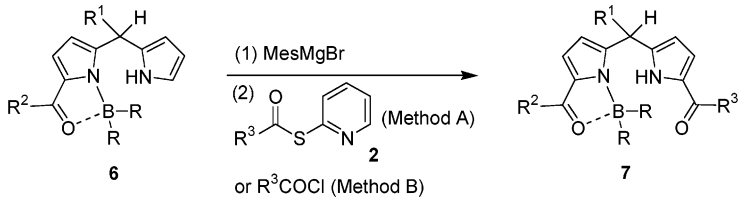
The 1-acyldipyrromethane−BR_2 complexes **6a**−**e** contained the 9-BBN unit as the complexing species. We previously showed that other dialkylboron entities could

(11) Walker F. W.; Ashby, E. C. *J. Am. Chem. Soc.* **1969**, *91*, 3845−3850.

(12) English, R. B.; McGillivray, G.; Smal, E. *Acta Crystallogr.* **1980**, *B36*, 1136−1141.

(13) Geier, G. R., III; Callinan, J. B.; Rao, P. D.; Lindsey, J. S. *J. Porphyrins Phthalocyanines* **2001**, *5*, 810−823.

SCHEME 3



6	R^1	R^2	R^3	R_2B	Product	Yield	
						Method A	Method B
6a	Ph	Ph	Ph	9-BBN	**7a**	79%	90%
6a	Ph	Ph	4-MeO-Ph	9-BBN	**7b**	76%	88%
6a	Ph	Ph	2,3,5,6-F4-Ph	9-BBN	**7c**	82%	92%
6b	H	Ph	Ph	9-BBN	**7d**	90%	90%
6b	H	Ph	*n*-pentyl	9-BBN	**7e**	80%	87%
6c	4-MeO-Ph	4-MeO-Ph	4-Br-Ph	9-BBN	**7f**	76%	79%
6d	*n*-pentyl	*n*-pentyl	Ph	9-BBN	**7g**	71%	64%
6e	4-TMS-C≡C-Ph	4-Br-Ph	4-I-Ph	9-BBN	**7h**	74%	69%
6a′	Ph	Ph	Ph	Bu_2B	**7i**	73%	78%
6f′	2,3-dimethylphenyl	4-I-Ph	Ph	Bu_2B	**7j**	78%	77%

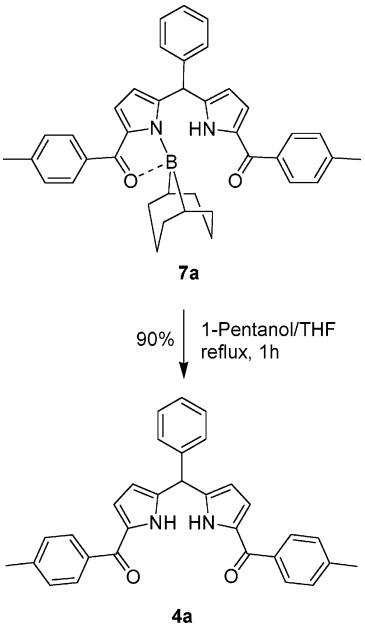
be employed for complexation of 1-acyldipyrromethanes.[5] While the 9-BBN species were generally preferred given the crystallinity of the resulting complexes, for particular substituents (e.g., 5-mesityl) the use of dibutylboron proved to be superior.[5] The 9-acylation procedure was applied to two 1-acyldipyrromethane−BBu_2 complexes (**6a′**, **6f′**). In each case, the 9-acylation proceeded smoothly to give the resulting 1,9-diacyldipyrromethane−BBu_2 complex (**7i**, **7j**) in good yield (Scheme 3).

The treatment of a 1-acyldipyrromethane−BR_2 complex with MesMgBr followed by addition of an acid chloride gave **7a**−**j** in comparable or higher yield versus that with a Mukaiyama reagent (Scheme 3). In the case of **6d** with *p*-toluoyl chloride as the acylating agent, the product **7g** was obtained in 64% yield with no chromatography.

Alternative Workup Procedures. 1-Acyldipyrromethane−BR_2 complexes (**6**) can be decomplexed in a straightforward manner by treatment with an alcohol, thereby affording the 1-acyldipyrromethane.[5] For ease of isolation, reaction with an alcohol such as pentanol is attractive, affording the relatively polar 1-acyldipyrromethane and the nonpolar 9-BBN pentyl ether. The same decomplexation procedure was examined for 1,9-diacyldipyrromethane−BR_2 complex **7a**. Treatment of **7a** with 1-pentanol/THF at reflux gave 1,9-diacyldipyrromethane **4a**, which was isolated in 90% yield without chromatography (Scheme 4).[5]

We previously showed that 1,9-diacyldipyrromethanes could be readily purified as a complex formed upon reaction with dibutyltin dichloride.[4] The same tin-complexation procedure was applied as a means of purifying the 1,9-diacyldipyrromethane from the crude mixture obtained upon 9-acylation of a 1-acyldipyrromethane−BR_2 complex. Thus, the crude reaction mixture derived from 9-acylation of **6a** with **2a** was treated with MeOH/THF (1:1) at reflux. Removal of the solvent, treatment of the residue with Bu_2SnCl_2 and TEA in CH_2Cl_2 at room

SCHEME 4

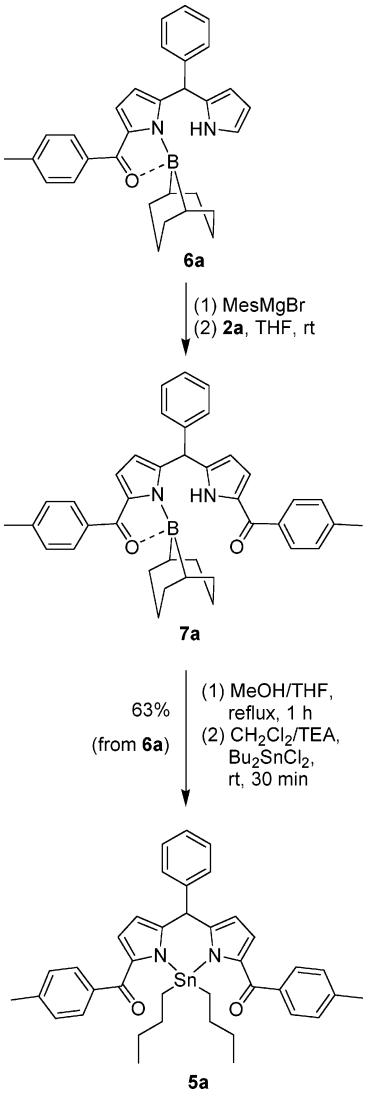


temperature, and purification by passing the mixture over a small pad of silica followed by crystallization afforded the 1,9-diacyldipyrromethane−dibutyltin complex **5a** in 63% yield (Scheme 5). The tin-complexation procedure affords a product with satisfactory elemental analysis but requires two extra steps and affords a slightly lower yield versus that in the direct isolation of the 1,9-diacyldipyrromethane−BR_2 complex.

Characterization. The 1,9-diacyldipyrromethane−BR_2 complexes typically were obtained as yellow solids (except **7g**), are nonpolar in nature, and are soluble in common organic solvents. In organic solvents (CH_2Cl_2, Et_2O, etc.) the 1,9-diacyldipyrromethane−BR_2 complexes slowly undergo decomplexation over a period of 1−3 days, forming the free 1,9-diacyldipyrromethane.

The ^{1}H NMR spectra of 1,9-diacyldipyrromethane−BR_2 complexes show (1) a characteristic downfield shift (∼1.2 ppm) of the pyrrolic NH resonance, (2) a ∼0.7 ppm downfield shift of the H^8 resonance, and (3) disappearance of the H^9 resonance (Chart 2). In some cases, the ^{1}H NMR spectra also showed peaks due to the presence of Et_2O or THF, even after prolonged vacuum desiccation of the solid sample. In one sample that we examined in detail, the 1,9-diacyldipyrromethane−BR_2 complex (**7a**, prepared by the HMDS procedure; see Supporting Information) was found by ^{1}H NMR analysis to contain one molecule of Et_2O per two molecules of the 1,9-diacyldipyrromethane−BR_2 complex. The elemental analysis results of this sample were found to be satisfactory upon taking into account the stoichiometric inclusion of Et_2O in the crystal lattice (one molecule of Et_2O per two molecules of the 1,9-diacyldipyrromethane−BR_2 complex). A similar phenomenon has been observed with 1-acyldipyrromethane−BR_2 complexes, where X-ray crystallography showed the presence of one molecule Et_2O per two molecules of the 1-acyldipyrromethane−BR_2 complex in the unit cell.[5] When the ^{1}H NMR analysis showed the presence of residual ethereal solvent, further purification was generally achieved by dissolving the 1,9-diacyldipyrromethane−BR_2 complex in CH_2Cl_2 and hexanes followed by removal of the solvent.

SCHEME 5



The workup procedures generally afforded a relatively pure product with minimal or no chromatography. Of the 20 1,9-diacyldipyrromethane−BR_2 complexes that were prepared (Scheme 3), satisfactory elemental analyses were obtained for 13 samples. Five of the remaining seven samples gave satisfactory elemental analyses assuming the presence of one molecule of water per two 1,9-diacyldipyrromethane−BR_2 complexes. The final two samples (each containing the BBu_2 moiety) did not give satisfactory elemental analyses. Regardless, each 1,9-diacyldipyrromethane−BR_2 complex exhibited a high-quality ^{1}H NMR spectrum and a satisfactory FABMS analysis.

X-ray structural analysis was performed on **7b**, a 9-BBN complex of a 1,9-diacyldipyrromethane bearing three distinct aryl substituents (Figure 1). (It is noteworthy that for this crystal, no solvent inclusion was observed in the crystal lattice, and a satisfactory elemental analysis was obtained.) The boron atom, α-carbonyl group, and the pyrrole unit in the complex are nearly coplanar. The C−O bond length (1.301 Å) is longer than that for the 2-benzoylpyrrole (1.234 Å),[12] suggesting some

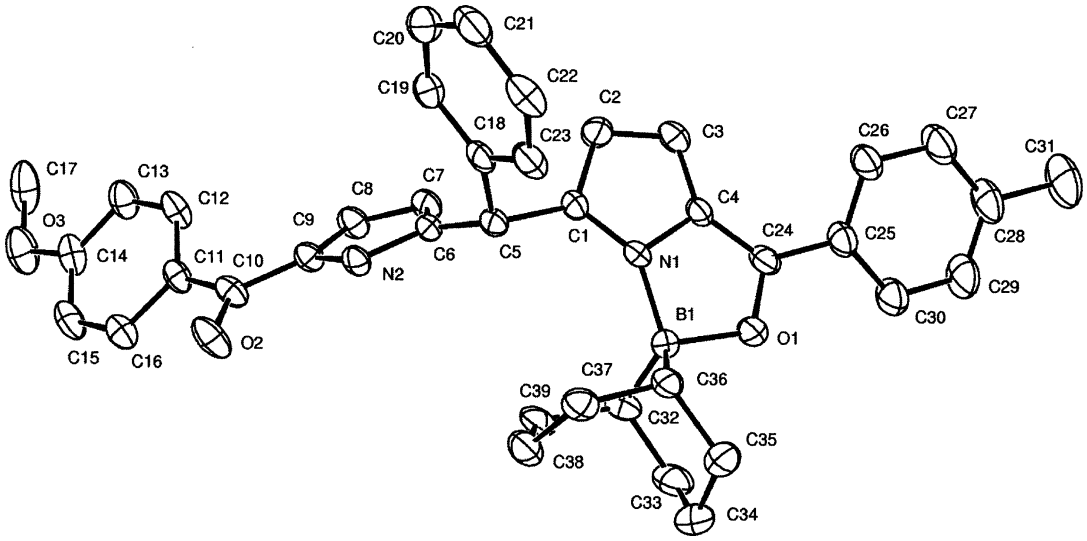


FIGURE 1. ORTEP drawing of the X-ray structure of **7b**. The diacyldipyrromethane bears three distinct aryl groups and one 9-BBN unit. All ellipsoids are contoured at the 50% level. Hydrogen atoms are omitted for clarity.

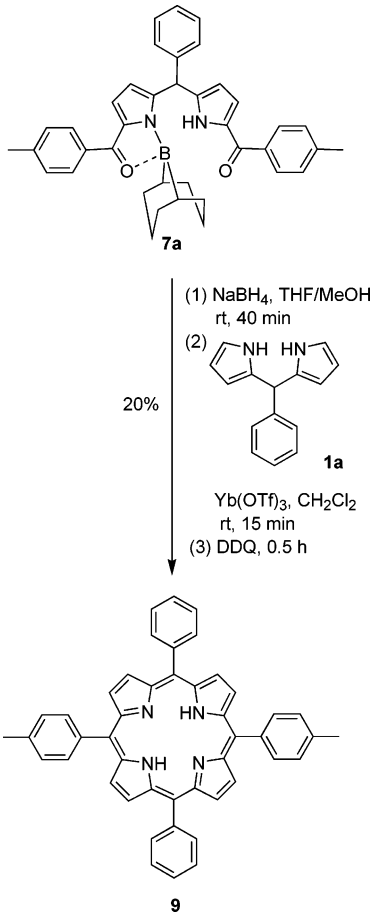
enolate character. The C−C bond between the carbonyl carbon and the α-carbon of the acylpyrrole (1.401 Å) is significantly shorter than that in 2-benzoylpyrrole (1.445 Å), also suggesting partial multiple bond character.[12] Similar structural features were reported for a 2-ketopyrrole−BF_2 complex[14] and a 1-acyldipyrromethane−BR_2 complex.[5]

Use of 1,9-Diacyldipyrromethane−Boron Complexes for Porphyrin Formation. The 1,9-diacyldipyrromethane−BR_2 complex **7a** was examined as a precursor in a porphyrin-forming reaction. Thus, the boron complex **7a** was treated with $NaBH_4$ in THF/methanol for 40 min. The reaction mixture was worked up in the standard way[1,3] and the product was subjected to acid-catalyzed ($Yb(OTf)_3$)[13] condensation with dipyrromethane **1a** followed by oxidation with DDQ. The corresponding porphyrin **9** was obtained in 20% yield (Scheme 6). No other porphyrin species were observed upon laser desorption mass spectrometry (LD-MS) analysis of the crude reaction mixture.

Bromination of a 1-Acyldipyrromethane−Boron Complex. 1-Bromo-9-acyldipyrromethanes are precursors to chlorin building blocks.[15] A 1-bromo-9-acyldipyrromethane is prepared by bromination of a 1-acyldipyrromethane. We sought to examine whether the 1-acyldipyrromethane−BR_2 complex could be brominated directly, thereby avoiding deprotection. Thus, treatment of **6a** with NBS in THF at −78 °C for 1 h afforded the desired 1-bromo-9-acyldipyrromethane as the 9-BBN complex **10** in 92% yield (Scheme 7). The success of this reaction is promising for the efficient and direct use of 1-acyldipyrromethane−BR_2 complexes in chlorin-forming reactions.

Outlook. The α-acylation of the pyrrole in a 1-acyldipyrromethane presents greater challenges than that of pyrrole itself. Indeed, in Nicolaou's synthesis of α-acylpyrroles using the pyrrolyl Grignard reagent and a

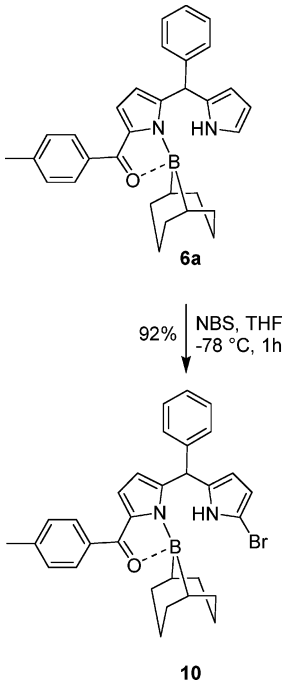
SCHEME 6



Mukaiyama reagent, a large excess (6 equiv) of the pyrrolyl Grignard reagent was employed.[16] In such syntheses, the Mukaiyama reagent was the more valuable species.[16,17] In the synthesis of 1,9-diacyldipyr-

(14) Chen, J.; Burghart, A.; Wan, C.-W.; Thai, L.; Ortiz, C.; Reibenspies, J.; Burgess, K. *Tetrahedron Lett.* **2000**, *41*, 2303−2307.
(15) Strachan, J.-P.; O'Shea, D. F.; Balasubramanian, T.; Lindsey, J. S. *J. Org. Chem.* **2000**, *65*, 3160−3172.
(16) Nicolaou, K. C.; Claremon, D. A.; Papahatjis, D. P. *Tetrahedron Lett.* **1981**, *22*, 4647−4650.
(17) Nakahara, Y.; Fujita, A.; Ogawa, T. *Agric. Biol. Chem.* **1985**, *49*, 1491−1495.

SCHEME 7



romethanes, the 1-acyldipyrromethane typically is the more valuable intermediate and is not available in excess. The strategy described herein provides an effective means of 9-acylation of a 1-acyldipyrromethane, using stoichiometric amounts of the 1-acyldipyrromethane and the acylating agent.

The 9-acylation method has an absolute requirement for (1) a mask of the α-acylpyrrole motif and (2) use of 2 molar equiv of a hindered Grignard reagent. Dialkylboron species such as dibutylboron or 9-BBN provide effective masks of the α-acylpyrrole motif. It is not clear why the α-acylpyrrole motif in the 1-acyldipyrromethane must be protected. However, use of excess MesMgBr with the uncomplexed 1-acyldipyrromethane did not afford efficient 9-acylation. The origin of the low yield of the reaction with the uncomplexed 1-acyldipyrromethane may stem from poor reactivity in an aggregate, or complexation of the two neighboring pyrrolic species in the 1-acyldipyrromethane. Regardless of mechanism, the combination of the 1-acyldipyrromethane−boron complex, 2 equiv of MesMgBr, and 1 equiv of acylating agent affords an excellent yield of the corresponding 1,9-diacyldipyrromethane−BR_2 complex.

Finally, while a variety of protecting groups have been employed for masking pyrrolic acyl groups or the pyrrolic nitrogen,[18] the dialkylboron complex provides an effective mask of both the α-acyl and pyrrolic nitrogen entities. The 1,9-diacyldipyrromethane−BR_2 complexes can be decomplexed smoothly under neutral conditions, or used directly in porphyrin syntheses. Reactions of the dialkylboron-masked 1-acyldipyrromethanes other than 9-acylation can be performed, such as 9-bromination. Further exploration is required to delineate the scope of accessible reactions in the presence of dialkylboron species as masking agents of the α-acylpyrrole motif.

(18) Toube, T. P. In *Pyrroles*; Jones, R. A., Ed.; John Wiley & Sons: New York, 1992; Part II, pp 1−129.

Experimental Section

Noncommercial Compounds. Dipyrromethanes **1a**−**e** were prepared as described in the literature and analyzed for purity by gas chromatography.[19] 1-Acyldipyrromethane **3a**,[3] 1-acyldipyrromethane−BR_2 complexes **6a**−**e**, **6a′**, and **6f′**,[5] and Mukaiyama reagent **2e**[13] were prepared as described in the literature.

Refined Synthesis of a Mukaiyama Reagent: *S*-2-Pyridyl 4-Methylbenzothioate (2a).[1] A solution of 2-mercaptopyridine (11.1 g, 100 mmol) in THF (100 mL) was treated with *p*-toluoyl chloride (15.5 g, 100 mmol) at room temperature. The resulting slurry was stirred for 30 min. The precipitate was collected by filtration and washed with hexanes (150 mL) in a Buchner funnel. The filtered material was added into 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 removed and the water layer was extracted with diethyl ether. The organic layers were combined, dried (Na_2SO_4), and filtered. The filtrate was concentrated to afford a pale yellow solid. The ^{1}H NMR spectrum of the yellow solid did not show any noticeable impurities. The yellow solid was dissolved in diethyl ether, and then hexanes was added causing formation of a precipitate. The precipitate was collected by filtration. The filtrate was concentrated forming a precipitate, which was collected. The resulting filtrate also was concentrated and the resulting precipitate was collected. The precipitates were combined, affording a colorless solid (22.3 g, 96%): mp 61−62 °C; ^{1}H NMR δ 2.43 (s, 3H), 7.26−7.35 (m, 3H), 7.70−7.81 (m, 2H), 7.89−7.95 (m, 2H), 8.64−8.70 (m, 1H). Anal. Calcd for $C_{13}H_{11}NOS$: C, 68.09; H, 4.84; N, 6.11. Found: C, 68.04; H, 4.78; N, 6.29. Note: Owing to the limited solubility of 2-mercaptopyridine, reactions that employed a solid acid chloride were performed at a concentration of 500 mM.

9-Acylation of a 1-Acyldipyrromethane−BR_2 Complex (Method A, Mukaiyama Reagent): 10-(9-Borabicyclo[3.3.1]-non-9-yl)-5-phenyl-1,9-di-*p*-toluoyldipyrromethane (7a). A suspension of **6a** (0.92 g, 2.0 mmol) in THF (2 mL) under argon was treated with mesitylmagnesium bromide (MesMgBr) (4.0 mL, 4.0 mmol, 1 M solution in THF), affording a clear solution that was stirred at room temperature for 5 min. Then a solution of **2a** (0.50 g, 2.2 mmol) in THF (2.2 mL) was added. The mixture was stirred at room temperature for 10 min under argon. The mixture was quenched by addition of a half-saturated aqueous solution of NH_4Cl (10 mL). Et_2O (20 mL) was added (Note 1). The organic layer was separated and washed with a saturated aqueous solution of $NaHCO_3$ (20 mL) followed by brine (10 mL). The organic layer was dried (Na_2SO_4) and concentrated to dryness under vacuum. The resulting brown residue was treated with a small amount of Et_2O (∼2−4 mL), affording a suspension consisting of a brown solution and a bright yellow powder. The resulting mixture was filtered on a Buchner funnel and washed with a small amount of hexanes (∼5−10 mL; Note 2). The filtered material (0.97 g, 84%, nearly pure; Note 3) was treated with CH_2Cl_2/hexanes (15 mL, 1:2) affording a suspension. The suspension was concentrated to one-fifth of the starting volume. The resulting mixture was filtered on a Buchner funnel. The precipitate was washed with hexanes to afford the title compound (0.92 g, 79%): mp 190−192 °C dec; ^{1}H NMR δ 0.68−0.74 (m, 2H), 1.66−2.28 (m, 12H), 2.42 (s, 3H), 2.48 (s, 3H), 6.00−6.02 (m, 1H), 6.10 (s, 1H), 6.46 (d, J = 4.4 Hz, 1H), 6.80−6.82 (m, 1H), 7.18 (d, J = 8.0 Hz, 2H), 7.25−7.38 (m, 8H), 7.77 (d, J = 8.0 Hz, 2H), 8.13 (d, J = 8.0 Hz, 2H), 9.10−9.12 (br, 1H); ^{13}C NMR δ 21.8, 22.2, 23.9, 25.2, 26.2, 26.3, 30.8, 31.0, 34.6, 34.7, 45.1, 127.6, 128.2, 128.5, 129.1, 129.2, 129.3, 130.0, 130.1, 131.2, 135.3, 135.9, 140.5, 141.0, 142.5, 145.4, 150.1, 175.2, 184.3; FABMS obsd 579.3224, calcd 579.3183 [$(M + H)^+$] ($M = C_{39}H_{39}BN_2O_2$). Anal. Calcd

(19) Laha, J. K.; Dhanalekshmi, S.; Taniguchi, M.; Ambroise, A.; Lindsey, J. S. *Org. Proc. Res. Dev.* **2003**, *7*, 799−812.

for $C_{39}H_{39}BN_2O_2$: C, 80.96; H, 6.79; N, 4.84. Found: C, 80.81; H, 7.00; N, 4.73.

Note 1: The highly crystalline nature of the 1,9-diacyldipyrromethane-BR_2 complex in diethyl ether often resulted in crystallization during the organic−aqueous partition in the separatory funnel. In such cases, the workup was performed with additional THF, or alternatively, by using CH_2Cl_2. In the latter case the organic layer should be washed twice with saturated aqueous $NaHCO_3$ to remove the 2-mercaptopyridine.

Note 2: Any 2-mercaptopyridine remaining after the Et_2O/hexanes wash can be removed by washing with a minimum amount of cold methanol on a Buchner funnel.

Note 3: In a number of cases, analysis of the product at this stage showed inclusion of ether or THF in the crystal lattice, and traces of 1-acyldipyrromethane−BR_2 complex and uncomplexed species (1-acyldipyrromethane, 1,9-diacyldipyrromethane). When no such trace species were present, the purification could be stopped at this stage, whereupon the product was isolated as a neat solid or as a solid containing the solvent inclusion. When the remaining purification steps were performed, the product was often isolated containing other included molecules (e.g., water, CH_2Cl_2, hexane).

9-Acylation of a 1-Acyldipyrromethane−BR_2 Complex (Method B, Acid Chloride): 10-(9-Borabicyclo[3.3.1]non-9-yl)-5-phenyl-1,9-di-*p*-toluoyldipyrromethane (7a). A suspension of **6a** (0.921 g, 2.00 mmol) in THF (2 mL) under argon was treated with MesMgBr (4.0 mL, 4.0 mmol, 1 M solution in THF). The mixture was stirred at room temperature for 5 min. Then a solution of *p*-toluoyl chloride (0.294 mL, 2.20 mmol) in THF (2.2 mL) was added. The mixture was stirred at room temperature for 10 min under argon. The mixture was quenched by addition of a half-saturated aqueous solution of NH_4Cl (10 mL). Et_2O (20 mL) was added. The organic layer was separated and washed with saturated aqueous $NaHCO_3$ (20 mL) followed by brine (10 mL). The organic layer was dried (Na_2SO_4) and concentrated to dryness under vacuum. The resulting yellow residue was treated with a small amount of Et_2O (∼2−4 mL), affording a suspension consisting of a brownish yellow solution and a bright yellow powder. The resulting mixture was filtered on a Buchner funnel and washed with a small amount of hexanes (∼5−10 mL) to afford the yellow powder (1.11 g, 96%, some decomplexed 1,9-diacyldipyrromethane was present; ∼2% as estimated by ^1H NMR spectroscopy). The yellow powder was treated with CH_2Cl_2/hexanes (15 mL, 1:2) affording a suspension. The suspension was concentrated to one-fifth of the starting volume. The resulting mixture was filtered on a Buchner funnel. The precipitate was washed with hexanes to afford the title compound (1.04 g, 90%): mp 190−192 °C dec; ^1H NMR δ 0.67−0.73 (m, 2H), 1.66−2.27 (m, 12H), 2.42 (s, 3H), 2.48 (s, 3H), 6.00−6.01 (m, 1H), 6.10 (s, 1H), 6.45 (d, J = 4.4 Hz, 1H), 6.80−6.82 (m, 1H), 7.18 (d, J = 8.4 Hz, 2H), 7.25−7.38 (m, 8H), 7.77 (d, J = 8.0 Hz, 2H), 8.13 (d, J = 8.0 Hz, 2H), 9.07−9.11 (br, 1H); ^{13}C NMR δ 21.8, 22.2, 23.9, 25.2, 26.2, 26.3, 30.8, 31.0, 34.6, 34.7, 45.1, 127.6, 128.2, 128.5, 129.1, 129.18, 129.24, 130.0, 130.1, 131.1, 135.3, 135.9, 140.5, 141.0, 142.5, 145.4, 150.0, 175.2, 184.3; FABMS obsd 579.3216, calcd 579.3183 [(M + H)$^+$] (M = $C_{39}H_{39}BN_2O_2$). The elemental analysis calcd for the sample assuming 0.5 mol equiv of water (Anal. Calcd for $C_{39}H_{40}BN_2O_{2.5}$: C, 79.72; H, 6.86; N, 4.77. Found: C, 80.13; H, 6.75; N, 4.85) is in good agreement with the observed data. Notes 1 and 3 (vide supra) also apply to this procedure.

Large-Scale Procedure for the 9-Acylation of a 1-Acyldipyrromethane−BR_2 Complex: 10-(9-Borabicyclo[3.3.1]-non-9-yl)-9-(*p*-methoxybenzoyl)-5-phenyl-1-*p*-toluoyldipyrromethane (7b). A suspension of **6a** (18.4 g, 40.0 mmol) in THF (40 mL) under argon was treated with MesMgBr (80.0 mL, 80.0 mmol, 1 M solution in THF) via syringe, affording a clear solution. The solution was stirred for 5 min at room temperature under argon. A solution of **2b** (10.79 g, 44.0 mmol) in THF (44 mL) was added via cannula under argon. The mixture was stirred at room temperature for 10 min. The reaction mixture was quenched by addition of a half-saturated aqueous solution of NH_4Cl (200 mL). Et_2O (150 mL) was added. The organic layer was separated and washed with saturated aqueous $NaHCO_3$ (2 × 150 mL) followed by brine (200 mL). The organic layer was dried (Na_2SO_4). Some precipitation was observed. The resulting suspension was filtered on Buchner funnel. The filtrate (#1) was set aside. The combined precipitate−Na_2SO_4 material was washed with Et_2O (50 mL) to remove impurities (filtrate #2). The combined precipitate−Na_2SO_4 material was extracted with CH_2Cl_2 to dissolve the product. Concentration of the CH_2Cl_2 solution afforded a yellow powder (6.70 g, 28%). Filtrates #1 and #2 were combined and concentrated to dryness under vacuum. The resulting brown residue was treated with Et_2O (20 mL), affording a suspension consisting of a brown solution and a bright yellow powder. The resulting mixture was filtered on a Buchner funnel and washed with hexanes (80 mL) to afford a yellow powder (14.9 g, 63%). The combined yield (21.6 g) is 91% (TLC and ^1H NMR spectroscopic analysis indicated the presence of a trace (<2%) of the decomplexed title compound; no further purification was performed): mp 190 °C dec; ^1H NMR δ 0.68−0.74 (m, 2H), 1.68−2.24 (m, 12H), 2.48 (s, 3H), 3.87 (s, 3H), 6.00−6.02 (m, 1H), 6.10 (s, 1H), 6.45 (d, J = 4.4 Hz, 1H), 6.80−6.82 (m, 1H), 6.96 (d, J = 8.0 Hz, 2H), 7.18 (d, J = 8.0 Hz, 2H), 7.26−7.38 (m, 6H), 7.89 (d, J = 8.0 Hz, 2H), 8.13 (d, J = 8.0 Hz, 2H), 9.08−9.14 (br, 1H); ^{13}C NMR δ 22.2, 23.9, 25.2, 26.3, 26.4, 30.7, 31.0, 34.6, 34.7, 45.1, 55.7, 111.3, 113.8, 118.5, 119.5, 120.8, 127.6, 128.2, 128.5, 129.0, 130.0, 130.1, 131.2, 131.3, 131.3, 135.2, 140.1, 141.1, 145.4, 150.2, 162.8, 175.2, 183.4; FABMS obsd 595.3150, calcd 595.3132 [(M + H)$^+$] (M = $C_{39}H_{39}BN_2O_3$). Anal. Calcd for $C_{39}H_{39}BN_2O_3$: C, 78.79; H, 6.61; N, 4.71. Found: C, 78.78; H, 6.63; N, 4.69. Notes 1−3 (vide supra) also apply to this procedure.

Decomplexation of a 1,9-Diacyldipyrromethane−BR_2 Complex: 5-Phenyl-1,9-di-*p*-toluoyldipyrromethane (4a). A solution of **7a** (0.29 g, 0.50 mmol) in THF (0.8 mL) was treated with 1-pentanol (0.2 mL). The reaction mixture was heated at reflux. After 1 h, TLC [silica, ethyl acetate/hexanes (1:4)] examination showed complete consumption of boron complex **7a**. The mixture was concentrated to dryness and the resulting oily residue was treated with 5 mL of hexanes to afford a light pink solid residue. The mixture was heated gently under reflux for 5 min (the solid dissolved completely). The mixture was cooled affording a precipitate upon standing for a few minutes. The solvent was decanted. The solid was dissolved in a minimal amount of CH_2Cl_2 (∼0.2 mL). Hexanes was added, causing precipitation. The resulting mixture was filtered on a Buchner funnel. The precipitate was collected and dried in vacuo to afford a light pink powder (0.075 g, 33%). The filtrate was concentrated by 4-fold. The resulting precipitate was filtered, dissolved in a minimal volume of CH_2Cl_2, and precipitated upon addition of hexanes, affording an additional 0.13 g of the title compound. The combined yield (0.206 g) is 90%: mp 110−112 °C (lit.[20] mp 75−76 °C); ^1H NMR δ 2.38 (s, 6H), 5.65 (s, 1H), 5.97−5.98 (m, 2H), 6.58−6.59 (m, 2H), 7.20 (d, J = 8.0 Hz, 4H), 7.31−7.33 (m, 1H), 7.34−7.42 (m, 2H), 7.48−7.50 (m, 2H), 7.70 (d, J = 8.0 Hz, 4H), 11.03−11.05 (br, 2H); FABMS obsd 458.1994, calcd 458.1969 [(M + H)$^+$] (M = $C_{31}H_{26}N_2O_2$).

9-Acylation Followed by Tin Complexation for Isolation of a 1,9-Diacyldipyrromethane: Dibutyl[5,10-dihydro-5-phenyl-1,9-di-*p*-toluoyldipyrrinato]tin(IV) (5). A solution of **6a** (0.46 g, 1.0 mmol) in THF (1 mL) was treated with MesMgBr (2.00 mL, 2.00 mmol, 1 M solution in THF). The mixture was stirred at room temperature for 5 min. Then a solution of **2a** (0.25 g, 1.1 mmol) in THF (1 mL) was added. The mixture was stirred at room temperature for 10 min. The mixture was quenched by addition of a half-saturated aqueous solution of NH_4Cl (10 mL). Et_2O (50 mL) was added. The

(20) Lee, C.-H.; Li, F.; Iwamoto, K.; Dadok, J.; Bothner-By, A. A.; Lindsey, J. S. *Tetrahedron* **1995**, *51*, 11645−11672.

organic layer was washed with aqueous $NaHCO_3$ (10 mL) and water, dried (Na_2SO_4), and concentrated to dryness under vacuum. The resulting orange residue was dissolved in THF (2 mL) and treated with methanol (2 mL). The mixture was heated at reflux for 1 h and then concentrated to dryness. The resulting brown oil was dissolved in CH_2Cl_2 (4 mL) and treated with TEA (0.418 mL, 3.00 mmol) and Bu_2SnCl_2 (0.304 g, 1.00 mmol) at room temperature for 30 min. The mixture was passed through a silica pad (CH_2Cl_2). The fast-moving yellow fractions were collected and concentrated to dryness. The residue was dissolved in a minimum amount of Et_2O. Then methanol was added, yielding a precipitate, which upon filtration afforded the title compound as a pale yellow solid (0.43 g, 63%): mp 157 °C dec; ^{1}H NMR δ 0.69 (t, J = 7.6 Hz, 3H), 0.74 (t, J = 7.6 Hz, 3H), 1.08−1.54 (m, 10H), 1.63−1.71 (m, 2H), 2.45 (s, 6H), 5.60 (s, 1H), 6.19 (d, J = 4.0 Hz, 2H), 7.09 (d, J = 4.0 Hz, 2H), 7.19−7.32 (m, 9H), 7.83 (d, J = 8.0 Hz, 4H). Anal. Calcd for $C_{39}H_{42}N_2O_2Sn$: C, 67.94; H, 6.14; N, 4.06. Found: C, 67.83; H, 6.13; N, 3.95.

Conversion of a 1,9-Diacyldipyrromethane−BBN Complex to a Porphyrin: 5,15-Diphenyl-10,20-di-*p*-tolylporphyrin (9). A sample of 1,9-diacyldipyrromethane−BR_2 complex **7a** (0.145 g, 0.250 mmol) was dissolved in dry THF/methanol (10:1, 11 mL) at room temperature in a round-bottomed flask fitted with a vented rubber septum and flooded with argon. The septum was removed as needed to add $NaBH_4$ (0.472 g, 12.5 mmol, 50 mol equiv) in small portions with rapid stirring. The progress of the reduction was monitored by TLC analysis [alumina, CH_2Cl_2/ethyl acetate (3:2)] of reaction aliquots. After the reaction was complete (about 40 min), the reaction mixture was poured into a stirred mixture of saturated aqueous NH_4Cl and CH_2Cl_2. The organic phase was separated, washed with water, dried (Na_2SO_4), and concentrated under reduced pressure to yield the dicarbinol as a foamlike solid. To the flask containing the dipyrromethane−dicarbinol (0.250 mmol assuming quantitative reduction) was added reagent grade CH_2Cl_2 (100 mL). To the same reaction mixture was added 5-phenyldipyrromethane (0.055 g, 0.250 mmol). The mixture was stirred for 5 min to achieve dissolution, and then $Yb(OTf)_3$ (0.206 g, 0.325 mmol) was added. The reaction was monitored by absorption spectroscopy, whereby a 25 mL reaction aliquot was injected into a solution of DDQ (300 mL, 0.01 M in toluene); then 25 mL of the resulting oxidized mixture was dissolved in CH_2Cl_2/EtOH (3:1, 3 mL), and the absorption spectrum was recorded. Then [elapsed time of 15 min after the addition of $Yb(OTf)_3$)] DDQ (0.08 g, 0.375 mmol) was added, and the mixture was stirred at room temperature for 0.5 h. Then TEA was added, and the entire reaction mixture was filtered (to remove quinone species) through a pad of alumina and eluted with CH_2Cl_2 until the eluant was no longer purple. The resulting porphyrin-containing solution was concentrated by rotary evaporation to give a purple solid. The solid was triturated with methanol and dried in vacuo to afford a crystalline purple solid (0.032 g, 20%). The characterization data (^{1}H NMR, LDMS, and UV−vis spectra) were consistent with the reported values.[4]

Bromination of a 1-Acyldipyrromethane−BBN Complex: 10-(9-Borabicyclo[3.3.1]non-9-yl)-1-bromo-5-phenyl-9-*p*-toluoyldipyrromethane (10). Following a procedure reported for the bromination of a 1-acyldipyrromethane,[15] a solution of **6a** (0.920 g, 2.00 mmol) in THF (20 mL) was cooled to −78 °C under argon. NBS (0.360 g, 2.02 mmol) was added and the reaction mixture was stirred for 1 h at −78 °C. Hexanes (10 mL) and water (10 mL) were added and the mixture was allowed to warm to room temperature. The organic phase was extracted with ether, dried (Na_2SO_4), and concentrated under reduced pressure without heating. The resulting yellow residue was chromatographed [silica, hexanes/CH_2Cl_2 (1:1)] to afford a yellow powder (0.994 g, 92%): mp 58 °C dec; ^{1}H NMR δ 0.64−0.72 (m, 2H), 1.64−1.88 (m, 6H), 1.94−2.24 (m, 6H), 2.48 (s, 3H), 5.74−5.78 (m, 1H), 5.96 (s, 1H), 5.95−6.08 (m, 1H), 6.41 (d, J = 4.0 Hz, 1H), 7.18 (d, J = 8.0 Hz, 2H), 7.24−7.41 (m, 6H), 7.70−7.74 (br, 1H), 8.12 (d, J = 8.0 Hz, 2H); ^{13}C NMR δ 22.2, 23.9, 25.2, 26.1, 26.4, 30.7, 30.8, 30.9, 34.56, 34.63, 44.9, 97.4, 110.2, 110.8, 118.3, 120.7, 127.4, 128.2, 128.5, 128.9, 129.9, 130.0, 133.9, 135.1, 141.6, 145.3, 151.0, 174.9; FABMS obsd 538.1807, calcd 538.1791 ($C_{31}H_{32}BBrN_2O$).

Acknowledgment. This work was supported 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 the NSF.

Supporting Information Available: Characterization data for all new compounds; ^{1}H NMR spectra for selected compounds; crystallographic data for **7b**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO048587D