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Direct Synthesis of Palladium Porphyrins from Acyldipyrromethanes

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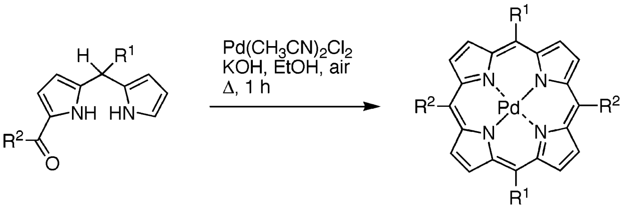

Palladium porphyrins are valuable photosensitizers and luminescent agents in biology and materials chemistry. New methodology is described wherein a 1-acyldipyrromethane is converted into the palladium chelate of a *trans*-A_2B_2 porphyrin via a one-flask reaction. The reaction entails self-condensation of the 1-acyldipyrromethane in refluxing ethanol containing KOH (5−10 mol equiv) and $Pd(CH_3CN)_2Cl_2$ (0.6 mol equiv) exposed to air. This direct route to palladium porphyrins is more expedient than the four steps of the traditional synthesis: (1) reduction of the 1-acyldipyrromethane; (2) acid-catalyzed condensation; (3) oxidation of the porphyrinogen intermediate; and (4) metal insertion. The new synthesis requires neither acid nor DDQ and formally entails only a $2e^- + 2H^+$ oxidation overall versus the traditional multistep synthesis which requires a $2e^- + 2H^+$ reduction per each 1-acyldipyrromethane ($4e^- + 4H^+$ overall) followed by a $6e^- + 6H^+$ oxidation. The analogous reaction of a 1,9-diacyldipyrromethane and a dipyrromethane also gives the palladium porphyrin. Seven palladium porphyrins have been prepared in yields of 25−57%. The direct route also can be used with $Cu(OAc)_2{\cdot}H_2O$ to give the copper porphyrin albeit in low yield. In summary, this methodology readily affords palladium porphyrins directly from acyldipyrromethanes.

Introduction

Pyrroles that bear α-acyl groups (such as pyrrole-2-carboxaldehyde) are known to form coordination complexes with a variety of metals [e.g., Cu(II), Ni(II), Pd(II), Pt(II)] and other ligands.[1] As part of a study aimed at developing a nonchromatographic method for purifying 1-acyldipyrromethanes (which contain the α-acylpyrrole motif), we screened a variety of metal reagents for formation of stable complexes of 1-acyldipyrromethanes. Dialkylboron reagents ultimately were found to serve as excellent complexation aids for the isolation of 1-acyldipyrromethanes from the crude acylation mixture.[2] In the course of this work, we made the surprising finding that some metal reagents, particularly those containing palladium and to a lesser extent copper, result in direct conversion of the acyldipyrromethane to the metalloporphyrin.

Palladium porphyrins are of interest owing to their high yield of intersystem crossing and long lifetime of the resulting triplet state in diverse media.[3] Palladium porphyrins have found applications as luminescent markers,[4] oxygen sensors,[5] sensitizers for singlet oxygen formation,[6] and photoinduced protein cross-linking agents.[7]

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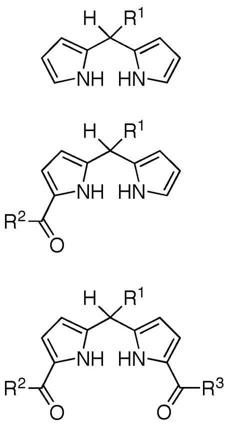
10.1021/jo050120v CCC: $30.25

CHART 1



1

2

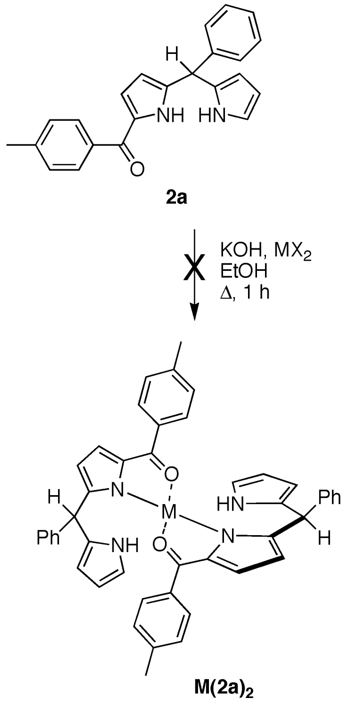
3

The first synthesis of palladium tetraphenylporphyrin (PdTPP) was reported in 1959.[8] Palladium porphyrins typically are prepared by metalation of the free base porphyrin using $PdCl_2$ in refluxing acetic acid,[8] $Pd(OAc)_2$ in refluxing benzonitrile,[9] or $Pd(OAc)_2$ in CH_2Cl_2/MeOH at room temperature.[6]

In this paper, we describe the results of the screen of a wide variety of metal reagents with 1-acyldipyrromethanes. We then focus on palladium and copper reagents and explore the scope of 1-acyldipyrromethanes that yield the *trans*-A_2B_2-porphyrin. The optimized conditions are applied to the reaction of a 1,9-diacyldipyrromethane + a dipyrromethane to give the corresponding porphyrin. The reactants thus include dipyrromethane (**1**),[10] 1-acyldipyrromethane (**2**),[2,11] and 1,9-diacyldipyrromethane (**3**)[12] species (Chart 1). These studies are complemented by an examination of optimal conditions for forming palladium porphyrins from the corresponding free base porphyrins. Taken together, this work provides new routes to palladium porphyrins. More broadly, this work identifies a new pathway to porphyrins that employs less reduced species (acyldipyrromethanes rather than dipyrromethanecarbinols), employs basic conditions, and does not require the use of a quinone oxidant.

Results and Discussion

1. Survey of Metal Reagents. A broad survey of metal reagents was performed using 1-(*p*-toluoyl)-5-phenyldipyrromethane (**2a**)[11] to identify suitable complexation aids for isolation of 1-acyldipyrromethanes. The metals examined include $Mg(OAc)_2{\cdot}4H_2O$, $Sc(OTf)_3$, TiF_4, $MnCl_2$, $Mn(OAc)_2$, $FeBr_3$, $Fe(OAc)_2$, $Fe(acac)_3$, $Co(OAc)_2{\cdot}4H_2O$, $Ni(OAc)_2{\cdot}4H_2O$, $Cu(OAc)_2{\cdot}H_2O$, $Zn(OAc)_2{\cdot}2H_2O$, GeI_4, $MoCl_3$, $RuCl_3{\cdot}H_2O$, $Pd(OAc)_2$, AgOTf, $CdCl_2$, $InCl_3$, $In(OAc)_3$, SnF_4, $SbCl_5$, $TeCl_4$, CeI_3, $EuCl_3$, $Dy(OTf)_3$, $Yb(OTf)_3$, $Pt(C_6H_5CN)_2Cl_2$, TlOAc, and $BiCl_3$. The expected complex (for divalent metals) is shown in eq 1. The survey was carried out under two conditions: (1) mild conditions at room temperature in methanol in the absence of base[2] or (2) more forcing conditions in refluxing ethanol containing excess base. The survey under the former conditions was generally unsuccessful but led eventually to the discovery of dialkylboron triflates as complexation aids.[2] The results of the survey under the latter conditions are presented herein.

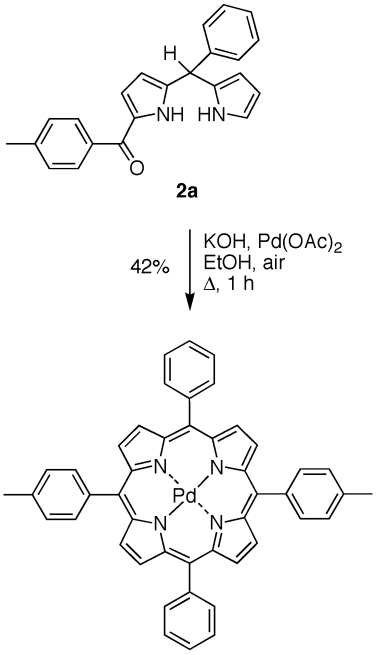


2a

(Eq 1)

M(2a)$_2$

A mixture of **2a** (42 mM) and KOH (420 mM) in ethanol was treated with a metal reagent at reflux for 1



2a

(Eq 2)

Pd-4a

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h. Most of the metal reagents examined either gave no reaction or formed multiple components. However, both Cu(OAc)$_2$·H$_2$O and Pd(OAc)$_2$ gave the corresponding metalloporphyrin. The reaction with Cu(OAc)$_2$·H$_2$O only afforded a trace of the copper porphyrin, but under more forcing conditions [**2a** (83 mM) and KOH (830 mM) in ethylene glycol (bp ~196−198 °C) containing Cu(OAc)$_2$·H$_2$O at reflux for 18 h in air] the copper porphyrin **Cu-4a** was obtained in 13% yield. The reaction of **2a** with Pd(OAc)$_2$ in refluxing ethanol (bp 78 °C) containing KOH exposed to air afforded the corresponding palladium porphyrin **Pd-4a** in 42% yield (eq 2). The formation of the Pd-porphyrin was confirmed by ^{1}H NMR spectroscopy, laser-desorption mass spectrometric (LD-MS) analysis,[13] and the characteristic visible absorption bands at 418 and 524 nm. No other porphyrin species were observed by LD-MS and TLC analysis.

2. Optimization of Reaction Conditions for Palladium Porphyrin Formation. A. Reagents. The self-condensation of **2a** in the presence of Pd(OAc)$_2$ and KOH in ethanol to give palladium porphyrin **Pd-4a** prompted a broader survey of conditions that encompassed the nature of the palladium reagent, the nature of the base, and the absolute requirement for various components. The general protocol entailed addition of ethanol to the three solids (1-acyldipyrromethane, palladium reagent, KOH) followed by heating exposed to air. The resulting mixture was heterogeneous, and palladium porphyrin often appeared as a purple film on the walls of the flask. Accordingly, yields were determined by removal of the volatile solvent, addition of a known quantity of THF to dissolve the porphyrin, followed by quantitative analysis by absorption spectroscopy.

The results of the survey are listed in Table 1. Among several palladium reagents, Pd(CH$_3$CN)$_2$Cl$_2$ afforded the highest yield (entries 1−6). The omission of palladium reagent or KOH resulted in no porphyrin (entries 7, 8). Indeed, omission of the palladium reagent while carrying out the reaction in refluxing 1-pentanol (bp 136−138 °C) gave no free base porphyrin even after 18 h, thus emphasizing the lack of reactivity of the 1-acyldipyrromethane in the absence of the palladium reagent (entry 9). The reaction was quite sensitive to the nature of the base, with poor results provided by TEA, NaH, and DBU (entries 10−13), though Ba(OH)$_2$·8H$_2$O gave porphyrin in yield comparable with that of the KOH reaction (entry 14). It is noteworthy that a number of the failed solvent/base combinations in entries 10 and 11 resemble those used with excellent success in Pd-mediated aerobic oxidation processes.[14−16] The reaction at room-temperature succeeded but was quite slow (entry 15). The effect of the number of equivalents of KOH (relative to **2a**) also was studied with the following results: 1 equiv, 5%; 2 equiv, 23%; 5 equiv, 53%; 10 equiv, 56% yield.

B. Order of Addition Effects. The typical order of addition was to combine the three solids (1-acyldipyrromethane, palladium reagent, KOH), add ethanol, then heat the resulting heterogeneous mixture exposed to air. On the other hand, when the palladium reagent was combined with a solution of ethanol and KOH (in the absence of the 1-acyldipyrromethane), a black precipitate formed. Addition of the 1-acyldipyrromethane **2a** to the mixture gave significant quantities of the free base 1-acyldipyrrin and only a small amount of porphyrin (2% yield at room temperature; 17% at 75 °C). The key finding from several experiments is that the precipitate formed upon interaction of the palladium reagent with ethanolic KOH alone is relatively inactive in the porphyrin-forming reaction (see the Supporting Information for a complete description of these experiments).

TABLE 1. Survey of Conditions for the Self-Condensation of 2a[a]

entry	variation from the standard conditions	yield of **Pd-4a**[b] (%)
1	none	55
2	Pd(acac)$_2$ in place of Pd(OAc)$_2$	55
3	Pd(CH$_3$CN)$_2$Cl$_2$ in place of Pd(OAc)$_2$	68
4	PdBr$_2$ in place of Pd(OAc)$_2$	5
5	PdCl$_2$ in place of Pd(OAc)$_2$	5
6	Pd(OH)$_2$ in place Pd(OAc)$_2$	0
7	omission of Pd(OAc)$_2$	0[c]
8	omission of KOH	0
9	omission of Pd(OAc)$_2$, refluxing 1-pentanol in place of EtOH, at reflux for 18 h	0[c]
10	TEA/THF, NaH/THF, pyridine/toluene[d] or NaOAc/DMSO[d] in place of KOH/EtOH	0
11	TEA/DME or NaOAc/DMSO in place of KOH/EtOH[e]	2−3
12	NaOMe/THF in place of KOH/EtOH, under Ar	0
13	DBU in place of KOH	12
14	Ba(OH)$_2$·8H$_2$O in place of KOH	55
15	Reaction at room temperature	48 (18 h)

[a] The standard conditions entail use of **2a** (0.125 mmol, 40 mM), KOH (1.25 mmol), and Pd(OAc)$_2$ (0.063 mmol) in refluxing ethanol exposed to air for 1 h. [b] The yield of porphyrin **Pd-4a** was determined spectroscopically (see the Experimental Section). [c] No free base porphyrin was observed, but a trace of 1-acyldipyrrin was observed (see the Supporting Information). [d] The reaction was performed using **2a** (0.10 mmol, 100 mM), base (0.50 mmol), Pd(OAc)$_2$ (0.06 mmol), and bubbling oxygen at 75 °C for 1 h. [e] The reaction was performed using **2a** (0.10 mmol, 100 mM), base (0.50 mmol), and Pd(OAc)$_2$ (0.06 mmol) at 65 °C exposed to air for 1 h.

C. Effect of Concentration. The effect of concentration was examined by performing the reaction of **2a** at concentrations ranging from 10 mM to 1 M in ethanol at 75 °C exposed to air for 1 h. The concentrations of KOH and Pd(CH$_3$CN)$_2$Cl$_2$ were altered as required to maintain fixed ratios with respect to the concentration of **2a**. Note that the term concentration is used to facilitate comparison even though the reaction mixtures generally are heterogeneous. The highest yields (48−65%) were obtained with **2a** in the range of 10−178 mM (Figure 1A).

D. Time Course. The formation of palladium porphyrin using **2a** (100 mM), KOH (500 mM) and Pd(CH$_3$CN)$_2$Cl$_2$ (60 mM) in ethanol at 75 °C exposed to air was examined over the course of 3 h. The maximum yield of porphyrin (53%) was obtained within 60 min and showed no significant change thereafter (Figure 1B).

E. Effect of Pd Oxidation State. The effect of different oxidation states of palladium [Pd(0), Pd(II), Pd(IV)] was examined under anaerobic conditions at 70 °C for 1 h. The Pd(0) and Pd(IV) oxidation states were probed using Pd(PPh$_3$)$_4$ and Na$_2$PdCl$_6$, respectively. Reactions were monitored over time, and the yields

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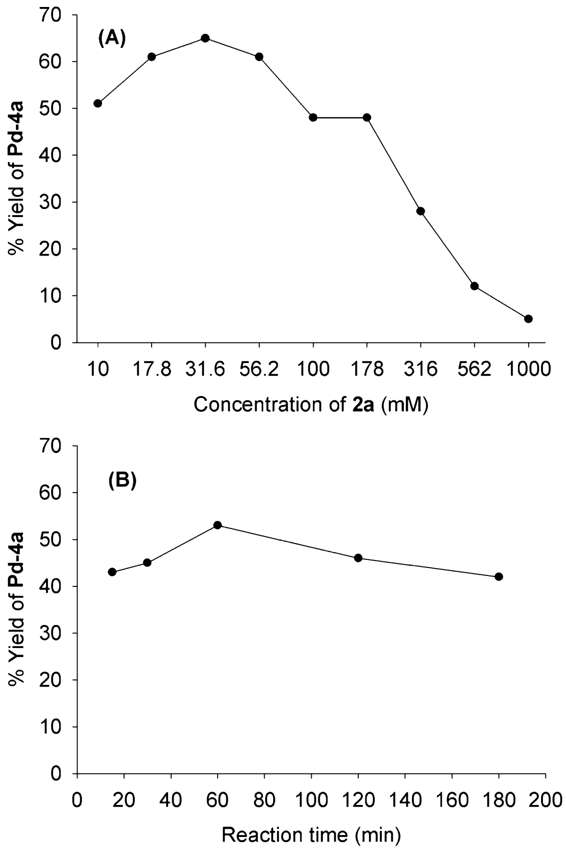

FIGURE 1. (A) Effect of concentration on the self-condensation of 1-acyldipyrromethane **2a** affording the palladium porphyrin. The yields were determined spectroscopically. The reaction was carried out in ethanol containing KOH and Pd($CH_3CN)_2Cl_2$ at 75 °C exposed to air for 1 h. The concentrations of KOH and Pd($CH_3CN)_2Cl_2$ were altered as required to maintain fixed ratios with respect to the concentration of **2a**. (B) Time course for the self-condensation affording the palladium porphyrin. The yields were determined spectroscopically. The reaction of 1-acyldipyrromethane **2a** (100 mM) was carried out in ethanol containing KOH (500 mM) and Pd(CH_3-$CN)_2Cl_2$ (60 mM) at 75 °C exposed to air.

TABLE 2. Effect of Pd Oxidation State on Porphyrin Formation[a]

reaction conditions	porphyrin yields[b] (%)		
	Pd(0)(PPh_3)$_4$	Pd(II)($CH_3CN)_2Cl_2$	Na_2Pd(IV)Cl_6
anaerobic	0	32, 32[c]	7[c]
anaerobic + DDQ[d]	0	27	12
aerobic	0	48, 53[c]	38, 35[c]

[a] Reaction of **2a** (100 mM) in ethanol containing the palladium reagent (60 mM) and KOH (500 mM) was performed for 1 h at 70 °C under the specified conditions, affording porphyrin **Pd-4a**. [b] Yields were determined spectroscopically (see the Experimental Section). [c] Isolated yield. [d] Reaction was performed under anaerobic conditions; samples were removed and treated with DDQ prior to yield determination via spectroscopy.

observed at 1 h are shown in Table 2. In the case of Pd(0), there was no porphyrin formed under anaerobic conditions even with subsequent DDQ oxidation, or under aerobic conditions. With Pd(IV), the porphyrin was isolated in 7% yield under anaerobic conditions but 35% yield under aerobic conditions. The results of the reactions with Pd(II) and Pd(IV) are quite similar under aerobic conditions.

In summary, the highest yields of palladium porphyrin were observed with a modest concentration of **2a** (31.6 mM) in hot ethanolic KOH (158 mM) containing Pd(CH_3-$CN)_2Cl_2$ (18.9 mM) exposed to air for 1 h. These conditions were identified by studies that employed yield determination via spectroscopic monitoring of the reactions. For scale-up purposes, the reaction at slightly higher concentration [**2a** (100 mM), KOH (500 mM) and Pd($CH_3CN)_2Cl_2$ (60 mM)] gave **Pd-4a** as a purple crystalline solid in 53% isolated yield. No other porphyrin species were observed upon LD-MS analysis of the crude reaction mixture.

3. Scope. A. Acyldipyrromethane Substituents. Exploration of the generality of the palladium porphyrin forming conditions required access to a set of 1-acyldipyrromethanes bearing a variety of substituents at the 1- and 5-positions. The 1-acyldipyrromethanes were prepared by reaction[11] of a dipyrromethane (**1a**–**c**)[10] with EtMgBr at −78 °C in THF followed by addition of a *S*-2-pyridyl thioate[17] (Mukaiyama reagent, **5a**–**e**) (Scheme 1). Each Mukaiyama reagent is known,[2,12,17,18] although the synthesis of **5e** was carried out under a refined procedure[12] by the reaction of mesitoyl chloride and 2-pyridylthiol. To facilitate purification of the 1-acyldipyrromethane, a boron-complexation strategy[2] was employed wherein the crude acylation mixture is treated with a dialkylboron triflate and TEA. The resulting hydrophobic dialkylboron complex of the 1-acyldipyrromethane can be isolated by precipitation/crystallization with limited or no chromatography. Dialkylboron complexes were obtained of **2a**–**d** and **2f**. A dialkylboron complex was not attempted for either **2e** or **2g**, which were prepared following a known procedure.[11,19] The 1-acyldipyrromethane-dialkylboron complexes **2-BR$_2$** were decomplexed by treatment with 1-pentanol in refluxing THF, affording the 1-acyldipyrromethanes. 1-Formyldipyrromethane **2h** was prepared following a known procedure.[20]

The generality of the palladium porphyrin forming conditions was examined with 1-acyldipyrromethanes **2b**–**h** (Scheme 2). The reaction conditions entailed the 1-acyldipyrromethane (100 mM), KOH (500 mM), and Pd($CH_3CN)_2Cl_2$ (60 mM) in ethanol at 75 °C exposed to air. The presence of electron-releasing rather than electron-withdrawing substituents at the 1- and 5-positions resulted in porphyrins with higher yields. The dipyrromethane with a 1-pentafluorobenzoyl group (**2c**) led to a porphyrin containing two ethoxy substituents in place of fluoro atoms. On the basis of the well-documented susceptibility of the para position of pentafluorophenyl groups to nucleophilic substitution,[21] the

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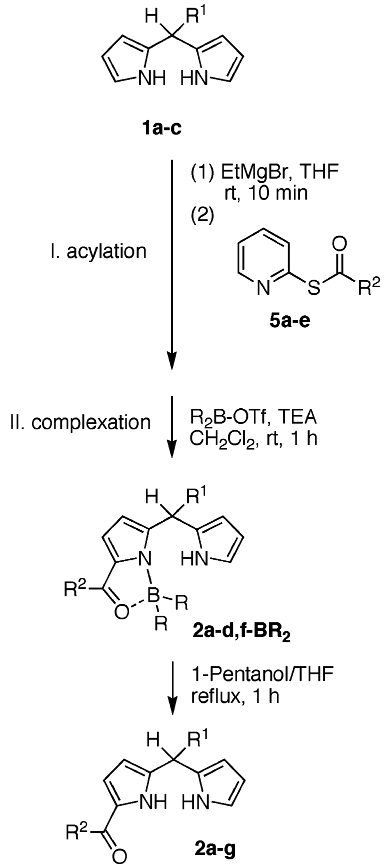
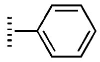
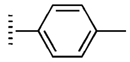
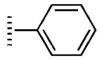
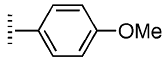
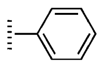
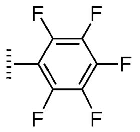
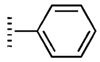
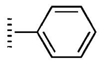
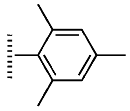
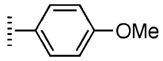
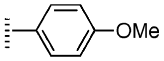
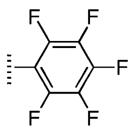
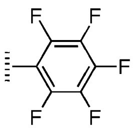
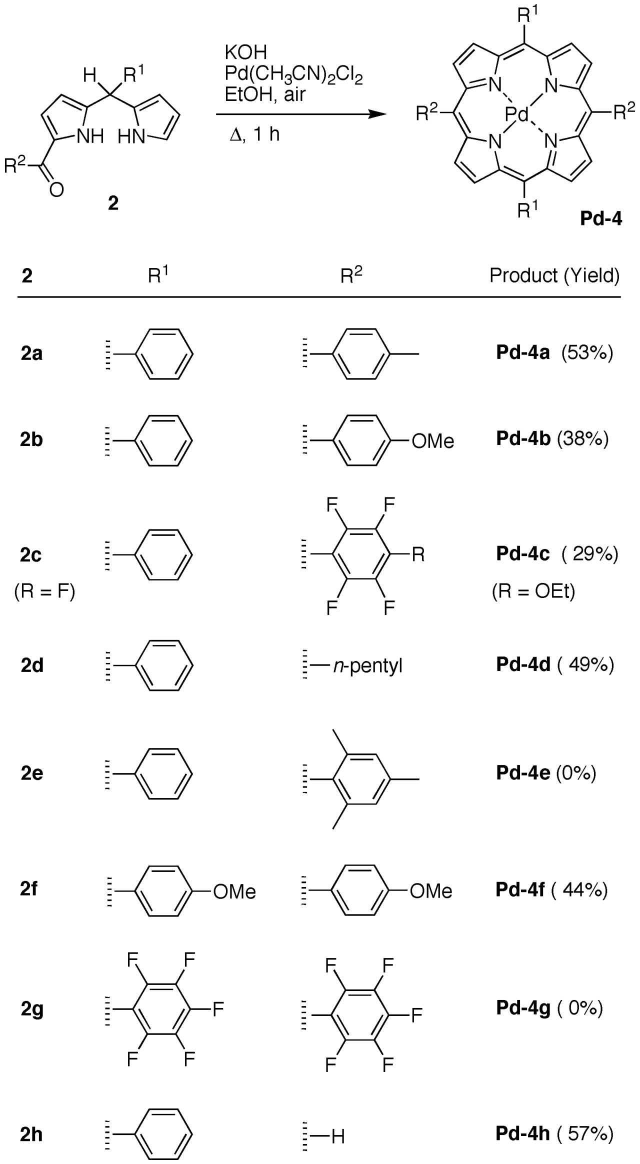
SCHEME 1



1	R^1	**5**	R^2	**2-BR$_2$** (Yield)	Product (Yield)
1a		**5a**		**2a-BBN** ref. 2	**2a** ref. 2
1a		**5b**		**2b-BBN** (62%)	**2b** (81%)
1a		**5c**		**2c-BBu$_2$** (55%)	**2c** (55%)
1a		**5d**	—*n*-pentyl	**2d-BBN** (42%)	**2d** (30%)
1a		**5e**		(no boron complex employed)	**2e** (67%)
1b		**5b**		**2f-BBN** ref. 2	**2f** ref. 2
1c		**5c**		(no boron complex employed)	**2g** ref. 19

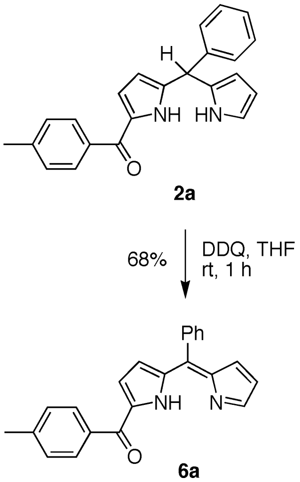
product is proposed as porphyrin **Pd-4c**. With the mesitoyl group in the 1-position of the dipyrromethane (**2e**), no palladium porphyrin was observed. The addition of DDQ also gave no porphyrin, thereby suggesting that the

SCHEME 2



failure of the reaction lies in condensation rather than oxidation processes. The reaction at elevated temperature (in 1-pentanol instead of ethanol) again showed no palladium porphyrin even after 18 h. In the case of **2g**, which contains pentafluorophenyl substituents in both the 1-acyl and 5-positions, a trace amount (~2%) of palladium porphyrin was observed spectroscopically but none was isolated. Neither addition of DDQ nor reaction at elevated temperature gave any porphyrin. Other than two failures, the isolated yields ranged from 29 to 57%. Among **Pd-4a**−**h**, only **Pd-4f**[22] has been prepared previously. Each palladium porphyrin was examined by fluorescence spectroscopy, which showed the absence of any contaminating free base porphyrin species.

B. Reactivity of Distinct Substrates. A variety of substrates related to 1-acyldipyrromethanes were examined under the standard reaction conditions, which generally entail the acylpyrrolic species (100 mM), $Pd(CH_3CN)_2Cl_2$ (60 mM), and KOH (500 mM) in ethanol at 75 °C exposed to air. All substrates examined were known compounds with the exception of 1-acyldipyrrin **6a**. The latter was obtained in 68% yield by the oxidation of 1-acyldipyrromethane **2a** with DDQ, in the same manner as for oxidation of dipyrromethanes[23] (eq 3). The results of the survey are shown in Table 3.



(Eq 3)

The self-condensation of a more reduced (dipyrromethane-1-carbinol **2a-OH**[11]) or more oxidized (1-acyldipyrrin **6a**) species gave the palladium porphyrin but in lower yield (22% or 23%) than for reaction with the 1-acyldipyrromethane **2a** (48%) (entries 1 and 2). The self-condensation of 2-benzoylpyrrole (**7**)[24] for 24 h did not give any of the corresponding porphyrin **PdTPP** (entry 3). The condensation of benzaldehyde with 5-phenyldipyrromethane (**1a**) or pyrrole proceeded poorly, affording the palladium porphyrin in 8% yield or not at all (entries 4 and 5). The condensation of 1,9-diacyldipyrromethane **3a**[12] with **1a** under the standard conditions gave palladium porphyrin **Pd-4a** in 27% yield (entry 6). The same 30 metal reagents as used in the initial survey (vide supra) were applied to the reaction of **3a** + **1a**, but no porphyrin was observed except in the case of $Pd(OAc)_2$, which afforded **Pd-4a** in 22% yield. The condensation of a 1,9-diacyldipyrrin (**8**)[25] with **1a** gave the Pd-porphyrin in 8% yield (entry 7). An attempt to decomplex the 1-acyldipyrromethane-BR_2 complex (**2a-BBN**)[2] in situ was examined by treating a suspension of **2a-BBN** in refluxing ethanolic KOH for 1 h, followed by addition of $Pd(CH_3CN)_2Cl_2$ with continued reflux for 1 h. The palladium porphyrin was observed in 22% yield (entry 8).

The success with palladium reagents prompted reexamination of congeners of palladium, although both $Ni(OAc)_2{\cdot}4H_2O$ and $Pt(C_6H_5CN)_2Cl_2$ were included in the initial survey. The use of $Ni(OAc)_2{\cdot}4H_2O$ or $Pt(C_6H_5CN)_2Cl_2$ in the self-condensation of **2a** under the optimized palladium porphyrin forming conditions using

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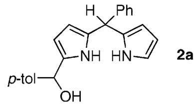
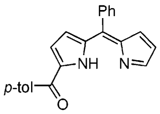
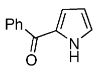
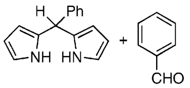
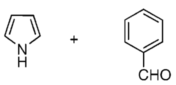
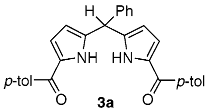
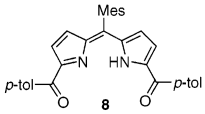
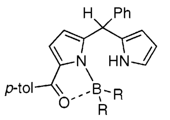
[22] Honeybourne, C. L.; Hill, C. A. S. *J. Phys. Chem. Solids* **1998**, *49*, 315−321.

[23] Yu, L.; Muthukumaran, K.; Sazanovich, I. V.; Kirmaier, C.; Hindin, E.; Diers, J. R.; Boyle, P. D.; Bocian, D. F.; Holten, D.; Lindsey, J. S. *Inorg. Chem.* **2003**, *42*, 6629−6647.

[24] (a) Jones, R. A.; Laslett, R. L. *Aust. J. Chem.* **1964**, *17*, 1056−1058. (b) Nicolaou, K. C.; Claremon, D. A.; Papahatjis, D. P. *Tetrahedron Lett.* **1981**, *22*, 4647−4650.

[25] Tamaru, S.-I.; Yu, L.; Youngblood, W. J.; Muthukumaran, K.; Taniguchi, M.; Lindsey, J. S. *J. Org. Chem.* **2004**, *69*, 765−777.

TABLE 3. Reactivity of Distinct Substrates Yielding Pd-Porphyrins

Entry	Reactant(s)	Conditions[a]	Expected porphyrin	Yield[b]
1	 **2a-OH**	1 h	**Pd-4a**	22%
2	 **6a**	24 h	**Pd-4a**	23%
3	 **7**	24 h[c]	**PdTPP**	0%
4	**1a** 	6 h[d]	**PdTPP**	8%
5		3 h[e]	**PdTPP**	0%
6	 **3a** + **1a**	1 h	**Pd-4a**	27% 25%[f]
7	 **8** + **1a**	1 h	**Pd-4i**	8%
8	 **2a-BBN**	1 h[g]	**Pd-4a**	22%

[a] The reactions were performed in ethanol containing the reactant (100 mM), KOH (500 mM), and Pd(CH_3CN)$_2$$Cl_2$ (60 mM) at 75 °C exposed to air for the specified time unless noted otherwise. The reactant **2a** gave **Pd-4a** in 48% yield under these conditions. [b] The yield of porphyrin was determined spectroscopically (see the Experimental Section). [c] The reaction employed Pd(CH_3CN)$_2$$Cl_2$ at 30 mM. [d] The reaction employed both **1a** and benzaldehyde at 100 mM. [e] The reaction employed pyrrole (400 mM), benzaldehyde (400 mM), KOH (1 M), and Pd(CH_3CN)$_2$$Cl_2$ (100 mM). [f] Isolated yield. [g] A suspension of **2a-BBN** (100 mM) and KOH (500 mM) in ethanol was refluxed for 1 h, followed by addition of Pd(CH_3CN)$_2$$Cl_2$ (60 mM) with continued reflux for 1 h.

refluxing 1-pentanol in the place of ethanol indicated ~1% metalloporphyrin formation by UV−vis analysis.

Application of the standard method to the synthesis of a chlorin afforded a mixture of porphyrin and chlorin, both in <3% yield (see the Supporting Information).

4. Reaction Course. Formation of the palladium porphyrin from the 1-acyldipyrromethane (**2**) in a one-flask process raises a number of questions concerning both porphyrin chemistry and palladium chemistry. The striking features from the porphyrin perspective are that the 1-acyldipyrromethane is reactive, the condensation occurs under basic conditions, and a quinone oxidant is not required. By contrast, the traditional synthesis of a metalloporphyrin from a 1-acyldipyrromethane entails four steps: (1) reduction of the 1-acyldipyrromethane to give the dipyrromethane-1-carbinol; (2) acid-catalyzed condensation of the dipyrromethane-1-carbinol; (3) oxidation of the porphyrinogen intermediate; and (4) metal insertion into the intact free base porphyrin. The two syntheses are outlined in Scheme 3.

The stepwise synthesis employs a 2 × ($2e^- + 2H^+$) reduction of the 1-acyldipyrromethane and a $6e^- + 6H^+$ oxidation of the resulting porphyrinogen, whereas the direct synthesis involves only a $2e^- + 2H^+$ oxidation overall (formally equivalent to oxidation of only one of the two 1-acyldipyrromethanes that participate in porphyrin formation). The presumed oxidant is molecular oxygen, although anaerobic reactions only diminished the yield by ~2-fold. Assuming that molecular oxygen acts as a $4e^- + 4H^+$ acceptor, self-condensation of 1 mmol of a 1-acyldipyrromethane stoichiometrically requires 0.25 mmol of O_2 (which corresponds to 6.1 mL of O_2 or 29 mL of air). The amount of oxygen dissolved in 10 mL of ethanol under an air atmosphere is 0.021 mmol (0.5 mL),[26] which is 12 times less than necessary, indicating that aeration of the reaction mixture is necessary. While no proof is in hand that molecular oxygen is the oxidant,

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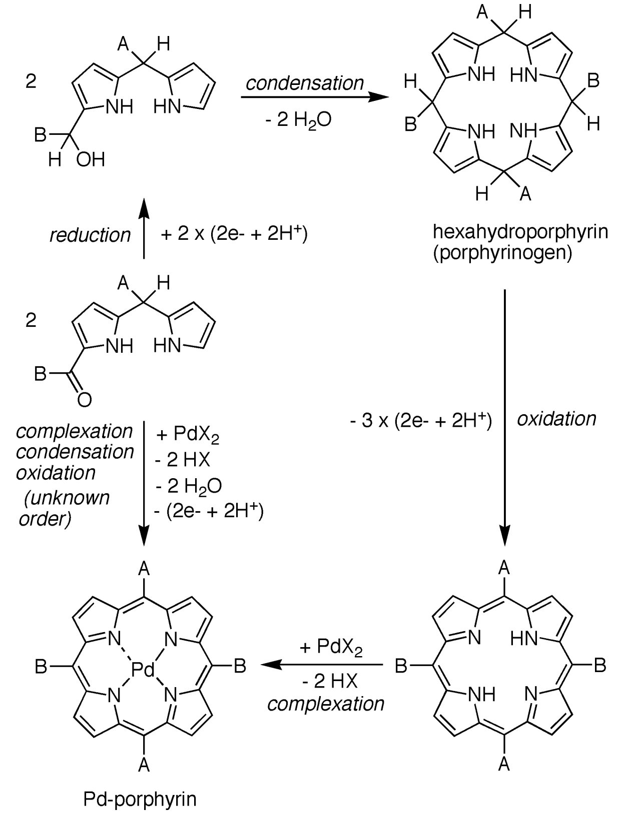
[26] Murov, S. L.; Carmichael, I.; Hug, G. L. *Handbook of Photochemistry*, 2nd ed.; Marcel Dekker: New York, 1993; p 290.

SCHEME 3



oxygen is a well-known oxidant in porphyrin-forming reactions at elevated temperatures,[27] and a number of Pd-catalyzed aerobic oxidations have been developed.[14-16]

The reaction yielding palladium porphyrins differs in several ways from other palladium-mediated reactions. (1) The structural changes accompanying conversion of the 1-acyldipyrromethane to the palladium porphyrin have no apparent analogue in the palladium literature. Some Pd-mediated aerobic oxidations entail C−C bond-forming reactions,[14-16] but the substrates are considerably different from 1-acyldipyrromethanes (although one reaction involves α-alkylation of indole[28]). (2) Pd-mediated reactions in general are designed to be catalytic in palladium with high turnover numbers, whereas the direct synthesis described herein results in inclusion of a stoichiometric quantity of Pd^{2+} in the reaction product as a stable coordination complex (the palladium porphyrin). (3) Attempts to use solvents and bases similar to those in Pd-mediated aerobic oxidations were generally unsuccessful (Table 1, entries 10 and 11). While an in-depth study of mechanism is beyond the scope of this paper, we pursued two lines of inquiry to address possible reaction intermediates.

A. Examination of a Calixpyrrole. One possible intermediate in the direct synthesis is a palladium-chelated 5,15-dihydroporphyrin, where the 1-acyldipyrromethane meso-position has remained untouched while C−C bond-formation occurred at the respective pyrrole and α-acyl positions. To determine whether a structure of this type would be plausible, we synthesized the corresponding calixpyrrole species having a geminal dimethyl group at the meso-position. Thus, 5,5-dimethyldipyrromethane (**1d**)[29,30] was subjected to 1-acylation with *S*-2-pyridyl benzothioate (**5f**,[11] prepared via a refined procedure[12]), affording the 1-acyldipyrromethane **2i** in 76% yield. Treatment of **2i** to the standard conditions for forming the palladium porphyrin did not give any isolated **Pd-9**, and subsequent quantitative analysis of the reaction mixture indicated that **Pd-9** was present in ~0.6% yield (see Supporting Information). On the other hand, reduction of **2i** gave **2i-OH**, which upon self-condensation under mild Lewis acid catalysis[31] gave the dihydroporphyrin **9** accompanied by calix[6]phyrin (**10**). An alternative route to **9**[32] and a route to analogues[33] of **9** and **10** have been reported. Treatment of **9** to new conditions for palladium insertion into free base porphyrins [$Pd(O_2CCF_3)_2$ in 1,2-dichloroethane/methanol (4:1) at 45 °C; vide infra] gave the corresponding palladium chelate **Pd-9** in 22% yield (Scheme 4).

The fact that **Pd-9** is only formed in trace quantity in the direct synthesis suggests the importance of removing the meso-proton in the 1-acyldipyrromethane, thereby generating a dipyrrin species, for the success of the direct synthesis. Whether dipyrrin formation entails a tautomerization involving the 1-acyl group (generating an enol) or an oxidation process is not known. It is worth noting, however, that exposure of a 1-acyldipyrromethane (**2a**) in ethanol/KOH at 70 °C to air (without any palladium reagent) gave no porphyrin and only a trace amount (~0.3%) of the corresponding 1-acyldipyrrin (**6a**). Thus, removal of the meso-proton does not occur to a significant degree in the hot, basic, aerobic conditions, but must be driven by interaction with a palladium species.

B. Isotopic Studies. The results in Table 3 show that species more reduced (dipyrromethanecarbinol **2a-OH**) or more oxidized (1-acyldipyrrin **6a**) than the benchmark 1-acyldipyrromethane **2a** undergo reaction to give the palladium porphyrin. We wondered whether PdX_2/KOH might cause reduction at the α-acyl position of the dipyrromethane, thus forming the dipyrromethanecarbinol (or a related palladium complex thereof), which could then react via the traditional path for porphyrin formation. Although reduction at the carbonyl group might seem at odds with the requirement for oxidation to give the porphyrin, the addition of the palladium reagent to ethanolic KOH in the absence of a 1-acyldipyrromethane results in a black precipitate (resembling those with reactions of Pd(0) species). The results from such omission experiments are described in the Supporting Information.

To probe reaction at the α-carbon position, we prepared a set of 1-acyldipyrromethanes and derivatives labeled

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[27] Adler, A. D.; Longo, F. R.; Shergalis, W. *J. Am. Chem. Soc.* **1964**, *86*, 3145−3149.

[28] Ferreira, E. M.; Stoltz, B. M. *J. Am. Chem. Soc.* **2003**, *125*, 9578−9579.

[29] Brown, W. H.; French, W. N. *Can. J. Chem.* **1958**, *36*, 371−377.

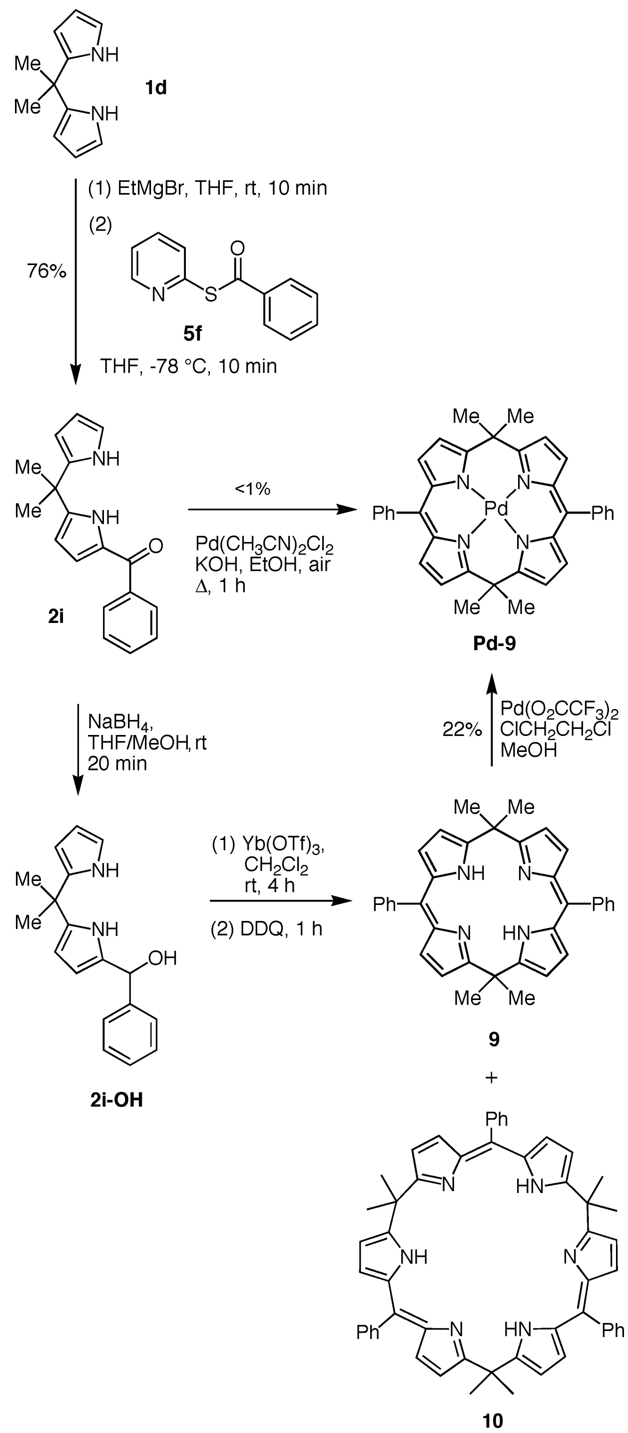
[30] Littler, B. J.; Miller, M. A.; Hung, C.-H.; Wagner, R. W.; O'Shea, D. F.; Boyle, P. D.; Lindsey, J. S. *J. Org. Chem.* **1999**, *64*, 1391−1396.

[31] Geier, G. R., III; Callinan, J. B.; Rao, P. D.; Lindsey, J. S. *J. Porphyrins Phthalocyanines* **2001**, *5*, 810−823.

[32] Hong, S.-J.; Ka, J.-W.; Won, D.-H.; Lee, C.-H. *Bull. Korean Chem. Soc.* **2003**, *24*, 661−663.

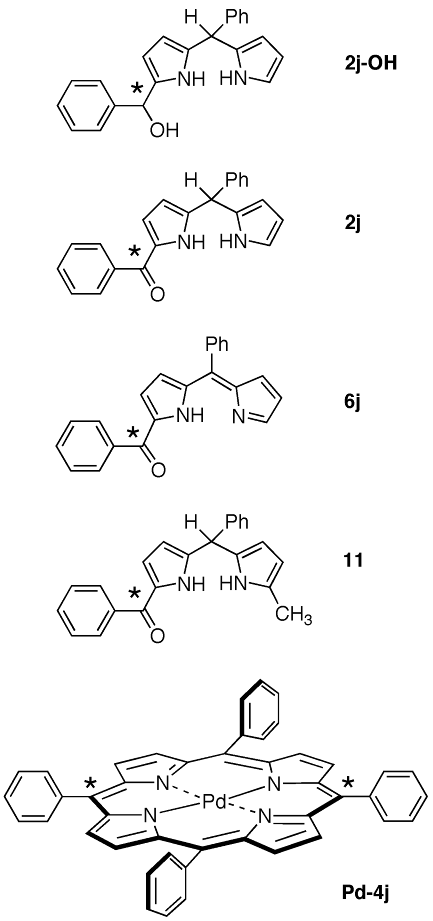
[33] Král, V.; Sessler, J. L.; Zimmerman, R. S.; Seidel, D.; Lynch, V.; Andrioletti, B. *Angew. Chem., Int. Ed.* **2000**, *39*, 1055−1058.

SCHEME 4



with ^{13}C at the α-position (acyl group or equivalent). The ^{13}C-labeled compounds include 1-acyldipyrromethane **2j**, the monocarbinol **2j-OH**, the 1-acyldipyrrin **6j**, an analogue of **2j** (**11**) wherein the 9-methyl group is present to block reaction and trap possible reaction intermediates, and the palladium porphyrin **Pd-4j** derived from **2j** (Chart 2). The syntheses follow the methods described herein and are presented in the Supporting Information. The chemical shift of the labeled carbon in each compound is as follows: **6j** (δ = 185.75 ppm); **2j** (δ = 184.75 ppm); **11** (δ = 184.0 ppm); **Pd-4j** (δ = 121.64 ppm); and **2j-OH** (δ = 70.36 and 70.45 ppm).

CHART 2



The reaction of **2j** under standard conditions afforded the corresponding ^{13}C-labeled palladium porphyrin **Pd-4j** in 42% yield. Studies of the reaction of **2j** at various temperatures (rt, 50 °C and 70 °C) with monitoring by ^{13}C NMR spectroscopy were inconclusive concerning specific intermediates; examination of the mixture at room temperature at 10 min after addition of $Pd(CH_3CN)_2Cl_2$ showed the peak characteristic of starting material **2j** (184.74 ppm) and of porphyrin **Pd-4j** (121.64 ppm), as well as three additional, unassigned peaks at 185.65, 185.80, and 185.95 ppm. Compound **11**, which cannot form the porphyrin, was examined similarly. TLC analysis of the reaction mixture showed several new less-polar components, the starting material, and extensive streaking from the origin. ^{13}C NMR spectroscopic examination of the crude reaction mixture upon dissolution in THF showed the expected peak of the ^{13}C-labeled carbonyl at 184.12 ppm, three low intensity peaks (184.37, 184.57, 184.69 ppm), and several other low intensity peaks of unknown origin throughout the ^{13}C NMR spectrum. Although specific intermediates were not identified, the reaction of **11** did not show any signal characteristic of a dipyrromethane-carbinol, though signals close to that of the dipyrrin **6j** were observed. Reactive intermediates such as a carbinol or other species may have low steady-state concentrations prohibiting detection by NMR spectroscopy. Thus, the overall pathway for the new synthesis remains to be determined.

5. Palladium Metalation. A traditional method for palladium insertion into free base porphyrins entails

TABLE 4. Effect of Solvents and Reagents on Palladium Insertion ($H_2TPP \rightarrow PdTPP$)[a]

solvent	$PdBr_2$	$Pd(OAc)_2$	$Pd(acac)_2$	$Pd(O_2CCF_3)_2$
$ClCH_2CH_2Cl$	0%	2%	7%	40%
$ClCH_2CH_2Cl$ +MeOH (4:1)	20%	6%	11%	80%
$ClCH_2CH_2Cl$ +Pyridine (5%)	0%	0%	0%	13%
THF	0%	20%	3%	70%

[a] The standard conditions entail use of H_2TPP (0.1 mmol, 50 mM) and palladium reagent (100 mM) at 60 °C for 1 h. Yields were determined spectroscopically via multicomponent analysis.

reaction of $Pd(OAc)_2$ in refluxing benzonitrile.[9] More recently, palladium metalation was achieved using $Pd(OAc)_2$ in CH_2Cl_2/MeOH at room temperature.[6] The latter results were followed up in an effort to determine the best choice of palladium reagent and solvent for the palladium insertion, using metalation of *meso*-tetraphenylporphyrin (H_2TPP) as the benchmark example. Analytical-scale reactions were performed using H_2TPP (0.1 mmol, 50 mM) and 2 equiv of a palladium reagent (100 mM) at 60 °C for 1 h. Among the different solvents and reagents examined, the best results were obtained with $Pd(O_2CCF_3)_2$ in 1,2-dichloroethane/methanol (4:1) or THF (Table 4), which afforded rapid metalation. The synthesis at larger scale afforded PdTPP in 64% isolated yield.

Outlook

The synthesis of a palladium porphyrin directly from self-condensation of a 1-acyldipyrromethane or condensation of a 1,9-diacyldipyrromethane + a dipyrromethane is in contrast with the four reaction steps (reduction, acid-catalyzed condensation, oxidation, and palladium insertion) of the traditional synthesis. The multistep synthesis involves a $2e^- + 2H^+$ reduction of each 1-acyldipyrromethane ($4e^- + 4H^+$ overall) followed by a $6e^- + 6H^+$ oxidation whereas the direct synthesis involves only a $2e^- + 2H^+$ oxidation overall. The direct synthesis avoids the use of acid (for condensation) and DDQ (for oxidation of the intermediate porphyrinogen). The use of basic reaction conditions avoids the tendency of dipyrromethanes to undergo cleavage, which is a source of scrambled porphyrinic products. The new reaction conditions also work to a modest extent for the synthesis of copper porphyrins. Although the mechanism of this heterogeneous reaction process remains to be elucidated, the simplicity of approach makes this strategy useful for preparing selected metalloporphyrins.

Experimental Section

I. Porphyrin-Forming Reactions. A. Spectroscopic Yield Determination. The palladium porphyrin forming reactions generally were heterogeneous. To assess the yield of the porphyrin-forming reactions, the entire reaction mixture was concentrated to dryness and then dried in vacuo. The residue was dissolved in a known amount of THF, and an aliquot from this solution was diluted in CH_2Cl_2/ethanol (3:1) solution, which was then examined by absorption spectroscopy. The yield of porphyrin was determined by the intensity of the Soret band (assuming $\epsilon_{Soret} = 300\,000$ M^{-1} cm^{-1}) measured from the apex to the inflection point at the base of the red edge of the band. Use of $\epsilon_{Soret} = 300\,000$ M^{-1} cm^{-1} was chosen on the basis of the reported range of ϵ_{Soret} values (80 000−337 000 M^{-1} cm^{-1}) for six palladium porphyrins[6] and the ϵ_{Soret} values (170 000−355 000 M^{-1} cm^{-1}) for eight palladium porphyrins prepared herein.

B. Analysis of Scrambling. The extent of scrambling in crude reaction mixtures or purified samples was determined by laser desorption ionization mass spectrometry (LD-MS) without a matrix.[13]

C. Reaction Media. Absolute ethanol was used in all studies of porphyrin formation. The reactions were carried out exposed to air unless noted otherwise. The reactions were carried out in ethanol at reflux or at 70 or 75 °C using temperature controllers. Such temperature control was generally employed to minimize solvent loss during experimentation in open vessels.

II. General Reaction Protocols. A. Screening of Metal Reagents for Metalloporphyrin Formation. (i) From a 1-Acyldipyrromethane. A solution of **2a** (43.0 mg, 0.125 mmol) in ethanol (3 mL) was treated with KOH (70.0 mg, 1.25 mmol) followed by the metal reagent (0.063 mmol). The mixture was stirred at reflux with exposure to air for 1 h. The reaction was examined by UV−vis spectroscopy and TLC (silica, CH_2Cl_2) for porphyrin formation. Yield determination was performed spectroscopically at the end of the reaction (see Section I.A).

(ii) From a 1,9-Diacyldipyrromethane + a Dipyrromethane. A solution of **3a** (57.0 mg, 0.125 mmol) and **1a** (28.0 mg, 0.125 mmol) in ethanol (3 mL) was treated with KOH (140 mg, 2.50 mmol) followed by the metal reagent (0.125 mmol). The mixture was stirred at reflux with exposure to air for 1 h. The reaction was examined by UV−vis spectroscopy and TLC (silica, CH_2Cl_2) for porphyrin formation. Yield determination was performed spectroscopically at the end of the reaction (see Section I.A).

B. Survey of Conditions (Solvents and Bases). A sample of **2a** (34.4 mg, 100 μmol) in a given solvent (1.0 mL) was treated with a base (0.5 mmol) followed by $Pd(OAc)_2$ (13.5 mg, 60.0 μmol). The mixture was stirred and heated with exposure to air for 1 h. Yield determination was performed spectroscopically at the end of the reaction (see Section I.A). The results are shown in Table 1.

C. Self-Condensation of a 1-Acyldipyrromethane: [5,15-Bis(4-methylphenyl)-10,20-diphenylporphinato]palladium(II) (Pd-4a). Samples of **2a** (0.340 g, 1.00 mmol), KOH (0.280 g, 5.00 mmol), and $Pd(CH_3CN)_2Cl_2$ (0.155 g, 0.600 mmol) were placed in a 25 mL round-bottom flask fitted with a condenser exposed to air. Ethanol (10.0 mL) was added, and the heterogeneous reaction mixture was stirred and heated to 75 °C for 1 h. The solvent was evaporated. The residue was dissolved in CH_2Cl_2 and passed through a pad of alumina (CH_2Cl_2). The resulting porphyrin-containing fraction was concentrated to give an orange-purple solid. The solid was triturated with methanol and dried in vacuo, affording a crystalline orange-purple solid (0.199 g, 53%): ^1H NMR δ 2.69 (s, 6H), 7.53 (d, $J = 8.0$ Hz, 4H), 7.70−7.81 (m, 6H), 8.04 (d, $J = 8.0$ Hz, 4H), 8.14−8.19 (m, 4H), 8.79 (d, $J = 5.1$ Hz, 4H), 8.83 (d, $J = 5.1$ Hz, 4H), (m, 8H); ^{13}C NMR δ 21.7, 121.8, 122.0, 126.9, 127.7, 127.9, 131.1, 131.2, 134.3, 134.3, 137.6, 139.0, 141.7, 141.9, 142.1; LD-MS obsd 746.3; FABMS obsd 746.1685, calcd 746.1661 ($C_{46}H_{32}N_4Pd$); λ_{abs} in nm (log ε) 418 (5.46), 464 (3.38), 485 (3.50), 524 (4.44), 554 (3.36).

D. Condensation of a 1,9-Diacyldipyrromethane with a Dipyrromethane, Affording Pd-4a. Samples of **1a** (0.111 g, 0.500 mmol), **3a** (0.229 g, 0.500 mmol), KOH (0.280 g, 5.00 mmol), and $Pd(CH_3CN)_2Cl_2$ (0.155 g, 0.600 mmol) were placed in a 25 mL round-bottom flask fitted with a condenser exposed to air. Ethanol (10.0 mL) was added, and the mixture was stirred and heated at 75 °C for 1 h. The solvent was evaporated. The residue was dissolved in CH_2Cl_2 and passed through a pad of alumina (CH_2Cl_2). The porphyrin-containing eluant was concentrated to give an orange-purple solid. The solid was triturated with methanol and dried in vacuo, affording a crystalline orange-purple solid (0.093 g, 25%) with satisfactory characterization data (^{1}H NMR, ^{13}C NMR, LD-MS and FABMS spectra) as described above.

E. Study of Pd Reagents in Distinct Oxidation States. (i) Method. Each reaction was carried out under an atmosphere of argon using a Schlenk line. The ethanol was degassed prior to use by several cycles of freeze−pump−thaw using a liquid nitrogen trap and an argon atmosphere. Standard reactions were performed in a 15-mL Schlenk tube in which the solid reagents were also degassed. The ethanol was cannulated into the reaction vessel and the resulting mixture was stirred at 70 °C for 1 h. The progress of the porphyrin-forming reactions was monitored by removing aliquots (25 μL) periodically from the reaction vessel via syringe. In some cases, the aliquots were injected into 300 μL of a 10 mM solution of DDQ in toluene. A 25-μL sample from this mixture was diluted in 3.00 mL of CH_2Cl_2/EtOH (3:l) and the visible absorption spectrum was recorded. The yield of porphyrin was determined by the intensity of the Soret band (assuming $\epsilon_{Soret} = 300\,000$ M^{-1} cm^{-1}) measured from the apex to the inflection point at the base of the red edge of the band. A set of determinations also was done with omission of DDQ, in which case the 25-μL reaction samples were diluted in 300 μL of CH_2Cl_2 and the resulting solution was further diluted in 3.00 mL of CH_2Cl_2/EtOH (3:l) to record the absorption spectrum. Note that reaction sampling in this manner entailed removal of samples from heterogeneous mixtures; isolated yields obtained in several instances gave general agreement with the observed trends.

(ii) Exemplary Reaction with Dichlorobis(acetonitrile)palladium(II). Samples of **2a** (0.17 g, 0.50 mmol), Pd($CH_3CN)_2Cl_2$ (77 mg, 0.30 mmol), and KOH (0.14 g, 2.5 mmol) were added to a Schlenk flask. The mixture was subjected to several cycles of degassing. Degassed ethanol was then added via cannula and the reaction mixture was heated to 70 °C. After 1 h, the spectroscopic yield was 32% without adding DDQ and 27% for the aliquots exposed to oxidation with DDQ. Then the mixture was concentrated and the resulting residue was dissolved in CH_2Cl_2 and passed through a pad of alumina (CH_2Cl_2). The resulting porphyrin-containing solution was concentrated to give an orange-purple solid. The solid was triturated with methanol and dried in vacuo, affording a crystalline orange-purple solid (60 mg, 32%): LD-MS obsd 746.0; FABMS obsd 746.1713, calcd 746.1662 ($C_{46}H_{32}N_4Pd$); λ_{abs} 416, 523 nm.

F. Oxidative Conversion of a 1-Acyldipyrromethane to a 1-Acyldipyrrin. 1-(4-Methylbenzoyl)-5-phenyldipyrrin (6a). Following a standard procedure,[23] a solution of **2a** (1.7 g, 5.0 mmol) in THF (16 mL) was treated dropwise with a solution of DDQ (1.13 g, 5.00 mmol) in THF (16 mL). After the mixture was stirred for 1 h at room temperature, the solvent was evaporated. The reaction mixture was dissolved in CH_2Cl_2 and purified by column chromatography [silica, CH_2Cl_2/ethyl acetate (25:1)] affording a pale brown amorphous powder (1.15 g, 68%): mp 120−122 °C; ^{1}H NMR δ 2.45 (s, 3H), 6.38 (d, $J = 4.0$ Hz, 1H), 6.57 (d, $J = 4.4$ Hz, 1H), 6.81 (d, $J = 4.4$ Hz, 1H), 6.82−6.84 (m, 1H), 7.30 (d, $J = 8.0$ Hz, 2H), 7.43−7.54 (m, 5H), 7.87 (d, $J = 8.0$ Hz, 2H), 8.09 (s, 1H), 12.90−13.40 (br, 1H); ^{13}C NMR δ 21.8, 119.1, 122.2, 125.4, 128.0, 129.2, 129.3, 129.5, 130.9, 135.0, 135.6, 136.7, 138.2, 139.3, 140.4, 143.1, 150.6, 159.6, 185.4; λ_{abs} (CH_2Cl_2) 302 nm (ϵ = 15,300 M^{-1}cm^{-1}), 432 nm (ϵ = 22,800 M^{-1}cm^{-1}). Anal. Calcd for $C_{23}H_{18}N_2O$: C, 81.63; H, 5.36; N, 8.28. Found: C, 81.70; H, 5.33; N, 8.24.

G. Palladium Insertion. (i) Survey of Conditions. A sample of *meso*-tetraphenylporphyrin (0.1 mmol, 50 mM) in a 4-mL conical reaction vial was dissolved in 2 mL of solvent. The palladium reagent (0.2 mmol, 100 mM) was added, and the mixture was stirred magnetically. Samples (1 μL) were removed periodically and diluted into toluene for absorption spectroscopy. TLC analysis was performed on silica (hexanes/CH_2Cl_2, 3:1). Multicomponent analysis over the range 450−750 nm was performed using known extinction coefficients for H_2TPP[34] and PdTPP.[6]

(ii) Preparative Synthesis of (*meso*-Tetraphenylporphinato)palladium(II) (PdTPP). A sample of H_2TPP (0.922 g, 1.50 mmol, 50 mM) in 1,2-dichloroethane/methanol (4:1, 30 mL) was treated with $Pd(O_2CCF_3)_2$ (0.997 g, 3.00 mmol), and the heterogeneous mixture was stirred and heated to 45 °C for 1 h. The mixture was chromatographed [alumina, hexanes/CH_2Cl_2, (2:1)]. The porphyrin fraction was concentrated to give an orange-purple solid. The solid was triturated with methanol and dried in vacuo, affording a crystalline orange-purple solid (0.690 g, 64%): ^{1}H NMR δ 7.69−7.80 (m, 12H), 8.14−8.22 (m, 8H), 8.81 (s, 8H); ^{13}C NMR δ 121.9, 126.9, 128.0, 131.2, 134.3, 141.7, 142.0; MALDI-MS (POPOP) obsd 719.0; FABMS obsd 718.1384, calcd 718.1349 ($C_{44}H_{28}N_4Pd$); λ_{abs} in nm (log ϵ) 417 (5.41), 485 (3.31), 523 (4.41), 554 (3.17).

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Supporting Information Available: Studies and results concerning reaction course (e.g., order-of-addition effects); synthesis of ^{13}C-labeled 1-acyldipyrromethanes; synthesis of a palladium chlorin; complete Experimental Section; spectral data for selected compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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