Oxidation of Heteroleptic Diarylpalladium Compounds with *tert*-Butyl Hydroperoxide. Substituent Effects in Aromatic Oxidation Reactions

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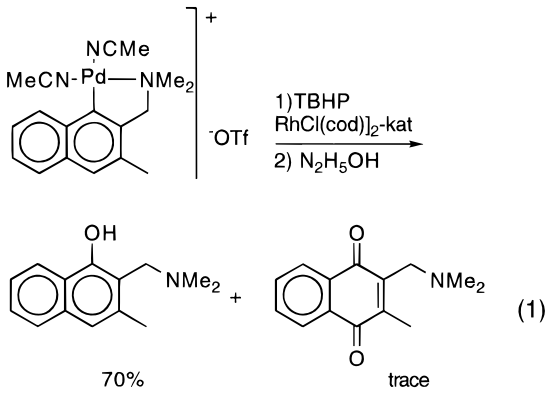
A series of heteroleptic diarylpalladium compounds, containing both a naphthyl (1-$C_{10}H_6$-CH_2NMe_2-2 or 1-$C_{10}H_5CH_2NMe_2$-2-Me-3) and a phenyl (1-$C_6H_4CH_2NMe_2$-2 or 1-$C_6H_3CH_2$-NMe_2-2-Me-*x*, *x* = 3, 5, 6) monoanionic C,N-bidentate ligand, was reacted with *tert*-butyl hydroperoxide (TBHP) to give selective oxygen insertion into one of the C−Pd bonds. It was found that the order of reactivity of the palladium−carbon bonds decreases in the order 1-naphthyl−Pd > phenyl−Pd. Introduction of methyl substituents enabled us to fine-tune the regioselectivity of the oxidation reactions (*i.e.* the ratio of phenyl- *versus* naphthyl oxygenation was affected) but not to reverse the order. The methyl groups have a deactivating influence on the aromatic substrates that contain them, indicating an oxidatively induced nucleophilic pathway for the actual oxygenation step. The yields of mono-oxygenated product RPdOR′ varied from 82 to 97% and were independent of the presence of a VO-$(acac)_2$ or $[RhCl(cod)]_2$ catalyst, although the reaction rates were strongly enhanced in the presence of these catalysts.

Introduction

The oxidation of hydrocarbons and, in particular, of aromatic hydrocarbons is an important reaction in organic synthesis.[1] A major disadvantage of most of the known oxidation procedures is low selectivity, as a result of the high reactivity of the oxidizing agent and the fact that the oxidation product is usually more susceptible to further oxidation than the original substrate. The use of platinum-metal catalysts for the selective hydroxylation of aromatic substrates is a fairly recent development. Furukawa has recently described the palladium-catalyzed conversion of benzene into phenol using molecular oxygen in acetic acid at 180 °C.[2] Strukul has developed a cationic platinum(II) complex catalyst which hydroxylates electron-rich aromatic substrates using 70% hydrogen peroxide as oxidant.[3] The stoichiometric insertion of oxygen into the Pd−C bond of palladated azobenzenes using *m*-chloroperoxybenzoic acid or iodosylbenzene as oxidant has been investigated by Chakravorty and Bandyopadhyay.[4] We have recently investigated the regio- and chemoselective palladation and subsequent oxidation (by *tert*-butyl hydroperoxide, TBHP) of derivatives of 2-[(dimethylamino)methyl]naphthalene.[5] For example, oxidation of the 1-palladated derivative [Pd(1-$C_{10}H_5CH_2NMe_2$-2-Me-3)$(MeCN)_2$]OTf in the presence of a catalytic amount of $VO(acac)_2$ or $[RhCl(cod)]_2$ stopped at the stage of the palladium 1-naphtholate intermediate (70% yield); only traces of further 1,4-oxidation were found (see eq 1).[5a]



(1)

In contrast, the 3-cyclopalladated compound [Pd(3-$C_{10}H_6CH_2NMe_2$-2)$(MeCN)_2$]BF_4 was cleanly 1,4-oxidized to the corresponding palladium bis(1,4-naphthoquin-3-olate) in 70% yield. Also, the oxidation of a symmetrical, bis(3-naphthyl)palladium compound proceeds with remarkably high selectivity, even in the absence of a catalyst (see eq 2).[5a]

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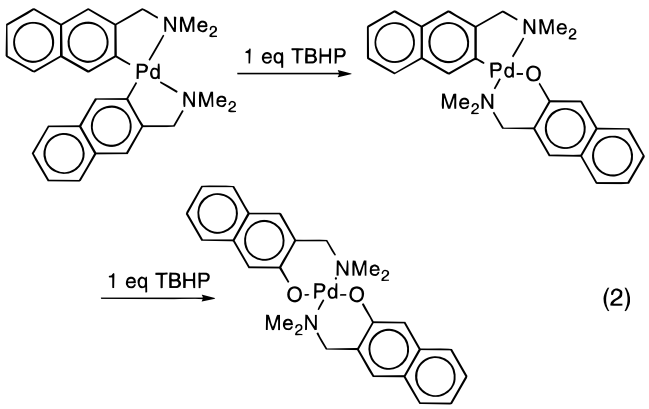


(2)

This compound reacts quantitatively with 1 equiv of TBHP to give a mono-oxygenated product with a selectivity of 90%. Use of excess TBHP resulted in the quantitative formation of the symmetrical bis-oxygenated product. Similar results were obtained in the oxidation of bis{2-[(dimethylamino)methyl]phenyl}-palladium.[6]

These high yields and selectivities prompted us to investigate the source of the selectivity of these oxidation. To that end, and also to study the differences in reactivity between naphthyl and phenyl substituents, we have prepared a series of heteroleptic diarylpalladium compounds containing a phenyl as well as a naphthyl substituent and studied their oxidation.

Results

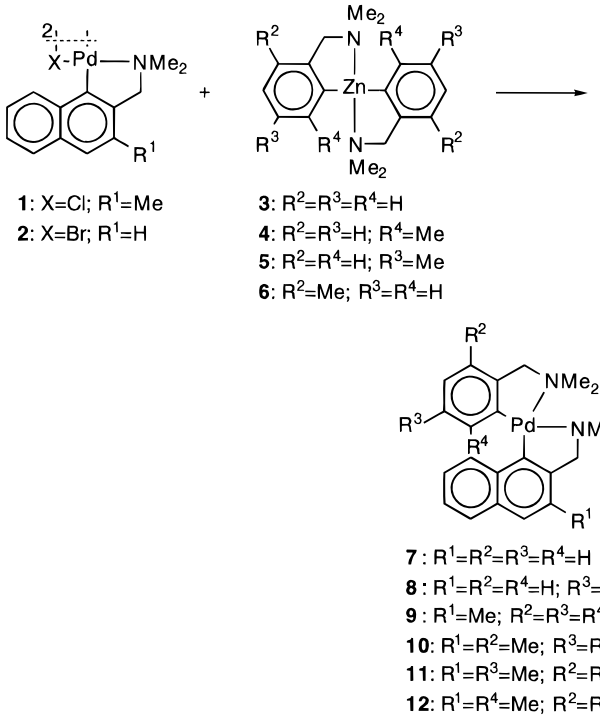
Synthesis of Heteroleptic Diorganopalladium Compounds. These compounds were obtained by reacting the appropriately substituted phenylzinc compounds with the corresponding 1-naphthylpalladium halides (Scheme 1). The latter were obtained by direct palladation of 2-[(dimethylamino)methyl]-3-methylnapthalene (for **1**) or oxidative addition of 1-bromo-2-[(dimethylamino)methyl]naphthalene to $Pd(dba)_2$ (for **2**).

The reactions proceed cleanly at room temperature in THF without formation of metallic palladium, and the products have been obtained in yields of more than 90%. Since both organic fragments are transferred from zinc to palladium, only 1 equiv of zinc compound is required to arylate 1 equiv of halogen-bridged palladium dimer. Although diarylzinc compounds are the reagents of choice for these preparations, aryllithium compounds may also be used. In that case the aryllithium compound has to be added to the arylpalladium compound at −78 °C to limit decomposition to less than 10% (quantitative decomposition does occur at room temperature). Once isolated, all diarylpalladium compounds described here are stable solids.

All diarylpalladium compounds containing the 1-{2-[(dimethylamino)methyl]naphthyl} substituent have characteristic NMR spectra. The CH_2 protons are diastereotopic and appear as AX patterns in the ^1H NMR spectrum, whereas two singlets are found for every NMe_2 fragment (Table 1). This confirms intramolecular coordination of the NMe_2 groups to palladium.

Synthesis of Arylpalladium Aryloxides. Independent synthesis of the potential product arylpalladium aryloxides RPdOR′ was carried out by adding a solution of the corresponding sodium phenolate or naphtholate in THF at room temperature to a solution of the arylpalladium chloride compound in THF (Scheme 2). All yields are higher than 95%. Selected ^1H NMR data are shown in Table 2. All CH_2 as well as NMe_2 protons appear as singlets in the ^1H NMR spectrum, except for compounds **7′**, **9′**, **11′**, and **12′**, where at room temperature the CH_2 protons appear as AB patterns close to the coalescence temperature.

Scheme 1



Oxidation Reactions. The oxidation of the diarylpalladium compounds **7**−**12** given in Scheme 1 was carried out in CH_2Cl_2 as solvent using 1 equiv of *tert*-butyl hydroperoxide (TBHP) as oxidant. A catalyst, *i.e.* $VO(acac)_2$[7] or $[RhCl(cod)]_2$,[8] may be added to the reaction mixture to enhance reaction rates. The yields were determined by isolation of the products and by ^1H NMR spectroscopy, using CH_2Cl_2 as internal standard. The products were analyzed either by direct comparison of NMR data with those of the independently prepared products or by NMR analysis of the free organic fragments after removal of palladium by hydrazine reduction. The latter method is somewhat less accurate, since both the nonoxidized and the oxidized derivatives of [(dimethylamino)methyl]benzene are rather volatile. GLC could not be used as an analytical method, since the naphthols 1-hydroxy-[2-(dimethylamino)methyl]-naphthalene **(2a)** and 1-hydroxy-3-methyl-[2-(dimethylamino)methyl]naphthalene **(3a)** are not sufficiently volatile. The results of the oxidation reactions, which proceeded with yields of 82−97%, are summarized in Table 3.

Discussion

Characterization of the Products. (Aryl)(aryloxy)-palladium(II) compounds are thought to have a *trans*

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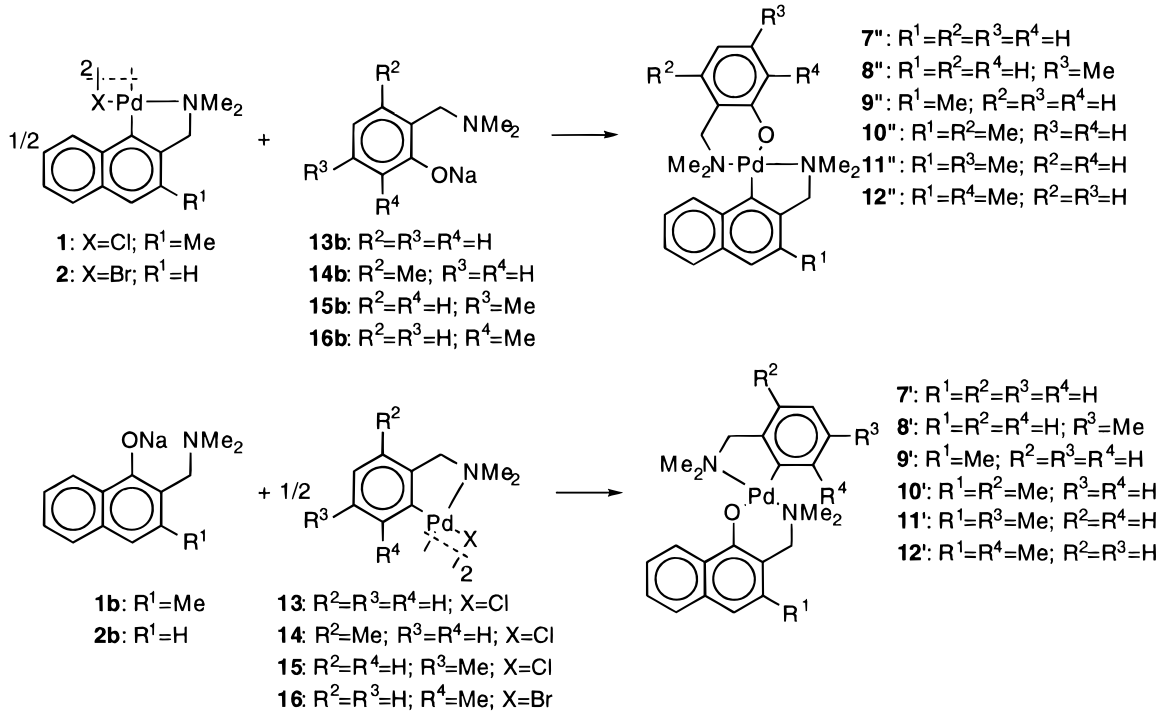
Scheme 2



configuration,[9] analogous to what recently was established for the structure in the solid state of Pd(C_6H_4-CH_2NMe_2-2)($OC_6H_4CH_2NMe_2$-2).[10] Because the six-membered N,O-chelate ring present in these compounds has a relatively low energy barrier to ring flip, the two CH_2 protons and the six $N(CH_3)_2$ protons in this ring will be homotopic sets at ambient temperature and appear as singlets in the ^{1}H NMR spectrum. This is indeed found for most of the present compounds, except for **7″**, **9″**, **11″**, and **12″** (*vide infra*). This is in marked contrast to the NMR spectra of the starting diaryl *cis* compounds. In the latter, the two aryl fragments are mutually held in rigid positions because of steric constraints and they consequently have a helical structure, making the prochiral CH_2 protons and the NMe_2 groupings diasterotopic.

The NMR spectra of the (1-naphthyl)(phenolato)-palladium compounds **7″**, **9″**, **11″**, and **12″** are different. At room temperature or slightly below, the signals for the CH_2 protons are AB or AX patterns. At higher temperature all signals are sharp singlets. This implies that at lower temperatures these groupings are diastereotopic, presumably by hindered ring flip of the N,O- and N,C-chelate rings. A common structural feature of these compounds is the presence of a 1-naphthyl substituent. Obviously, the five- and six-membered chelate rings in these four compounds or, in other words, the two planes formed by the aromatic systems are relatively fixed. The resulting fixed conformation renders the NMe_2 group stereogenic, and both the CH_2 and NMe_2 protons are diastereotopic. In compounds containing both a 1-naphthoxy and a phenyl substituent, only steric interaction between the substituent R^4 (see Scheme 2) and the NMe_2 group of the 1-naphthoxy substituent can force one of the chelate rings into a fixed conformation. In compounds containing both a 1-naphthyl and a phenoxy substituent, an interaction may be anticipated between naphthyl H(8) and the NMe_2 grouping of the phenoxy fragment. Apparently this latter interaction is larger in compounds **7″**, **9″**, **11″**, and **12″** than the former in, for example, compound **8**, in which R^4 = H. However, compound **12′** ($R^1 = R^4 =$ Me) also shows only signals from homotopic CH_2 and NMe_2 protons.

Oxidation of Diarylpalladium Compounds. It is well-known that naphthalene derivatives are generally more susceptible to electrophilic attack than benzene derivatives because the aromatic stabilization of naphthalene *per* ring is lower than for benzene.[11,12] For naphthalenes, the α-positions 1, 4, 5, and 8 are more susceptible than the *β*-positions 2, 3, 6, and 7 as a result of a more effective delocalization of the positive charge in the transition state of electrophilic attack (Wheland complex).[13] Also, in (aryl)palladium compounds the $Pd^{\delta+}-C_{ipso}\delta^-$ bond is polarized and oxygen insertion into the Pd−C bond will be influenced by the charge density on the C_{ipso} atom, which itself is influenced by mesomeric and inductive effects.

We have studied these effects by introducing methyl substituents on selected positions in the aromatic rings. The results of the oxidation of diarylpalladium compounds using 1 equiv of TBHP are summarized in Table 3.

In the oxidation of the unsubstituted (1-naphthyl)-phenylpalladium compound **7** the expected excess naph-

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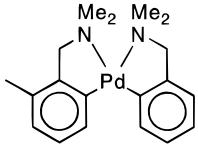
thyl group oxidation (80%) took place. However, substantial (i.e. 50%) phenyl group oxidation occurred in the case of the (3-methyl-1-naphthyl)phenylpalladium compound **9**. The methyl group in position 3 of the naphthalene system in **9** will enhance the electron density at C_{ipso}, even though the positions *ortho* and *para* to the electron-releasing group will be affected more strongly. This lower selectivity for the naphthyl substituent indicates that a higher negative charge on C_{ipso} leads to a lower susceptibility for oxygenation. Compound **10**, having a *meta* Me group in both the phenyl substituent and the naphthyl group, showed exactly the same selectivity as was found for **7**.

Besides electronic factors, steric effects may also be active. A methyl group *ortho* to the Pd−C bond can shield this bond or the Pd center for attack by the oxidant. On the other hand, Pd−C bond oxygenation can be enhanced because this step, which leads to a Pd−O−C bond arrangement, decreases the steric strain between the methyl group and the substituents attached to palladium. A 3-methyl group in the naphthyl ring *ortho* to the CH_2NMe_2 moiety and *meta* to the Pd center, as in compounds **9**−**12**, may negatively influence the rate of oxygenation, since in this process the five-membered chelate ring increases from five- to 6-membered, thereby forcing the CH_2NMe_2 moiety into the vicinity of the Me group. Several reactions exemplifying this last influence exist.[14] The changes in selectivity as one goes from the (1-naphthyl)palladium compound **7** to the (3-methyl-1-naphthyl)palladium derivative **9** may therefore also (partially be explained by a buttressing effect between the Me and the CH_2NMe_2 substituent. The oxygen migratory insertion into the Pd−C bond then has to be reversible to enable the oxygen to differentiate between the naphthyl and phenyl substituents.

When the (3-methyl-1-naphthyl)(5-methyl-1-phenyl)palladium compound **11** is compared with the (3-methyl-1-naphthyl)(3-methyl-1-phenyl)palladium compound **10**, both only differing in the location of the methyl group on the phenyl ring, we found only insignificant differences. Apparently, buttressing effects have at best a minor influence on the selectivity of oxidation.

So far, substituent effects have been investigated on different systems; *i.e.*, substituted phenyl and naphthyl groups have been compared. To obtain a more objective insight into the effects determining regioselectivity, Pd(1-$C_6H_4CH_2NMe_2$-2)(1-$C_6H_3CH_2NMe_2$-2-Me-3) **(17)**, containing a phenyl group with and one without a Me group *meta* to the palladium center, was reacted with TBHP. It appeared that the unsubstituted aromatic ring is only slightly favored (55:45). This implies that methyl groups are only capable of fine-tuning the selectivity already existing between different arene groupings.



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Conclusions

We have found that the introduction of an electron-releasing methyl group onto a phenyl ring decreases the relative yield of the phenolate formed by oxygenation of this ring. This is an unexpected result in view of the electrophilic nature of the oxygen transfer. The deactivating effect that the introduction of a methyl group has on the oxy functionalization of the aromatic ring to which it is attached is likely of electronic origin, since this effect is observed even when the methyl group is present at a position remote from the Pd center. Since the overall rate of oxygenation *increases* with the nucleophilicity of the Pd center, whereas electron-releasing methyl groups *decrease* the susceptibility to oxygenation of the aromatic ring to which they are attached, it seems that the oxygenation of organopalladium compounds occurs in two distinct steps. We propose that the interaction of peroxides with diarylpalladium(II) species first leads to formation of an organopalladium(IV) oxo complex by electrophilic oxygen transfer from the peroxide to the metal center and that oxygen migratory insertion into the Pd−C bond occurs from this Pd(IV) oxo intermediate in a second, regioselectivity-determining step which has nucleophilic character and is therefore hindered by introduction of electron-donating methyl substituents on the aromatic ring. The actual oxygen insertion may be formulated as an oxidatively induced nucleophilic substitution, with the Pd(IV) center acting as a strongly oxidizing leaving group in the attack of the nucleophilic oxo oxygen atom on the *ipso* carbon atom.[10]

The introduction of methyl groups does seem to enlarge the difference in reactivity but is incapable of reversing the order. The amount of 1-naphthyl oxidation varies with the presence of Me groups but is never lower than the amount of phenyl-oxidized product.

Experimental Section

General Comments. All reactions were performed under an atmosphere of dry, deoxygenated nitrogen using standard Schlenk techniques. All solvents, except MeOH, were dried prior to use. CH_2Cl_2 was dried on CaH_2 or anhydrous $CaCl_2$. ^1H and ^{13}C NMR spectra were recorded at 200 or 300 MHz in $CDCl_3$. Elemental analyses were carried out by Dornis und Kolbe, Mikroanalytisches Laboratorium, Mülheim a.d. Ruhr, Germany.

Ligand Syntheses. 2-Methyl-1-[(dimethylamino)methyl]benzene, 4-methyl-1-[(dimethylamino)methyl]benzene, and 2-bromo-3-methyl-1-[(dimethylamino)methyl]benzene[15] were prepared by reaction of Me_2NH with the corresponding benzyl bromides.[5b] 1,3-Dichloro-2-[(dimethylamino)methyl]benzene was prepared by reaction of Me_2NH with α,1,3-trichlorotoluene (bp 104 °C, 0.4 mmHg). All yields were >95% after purification by flash distillation. 2-Methyl[(dimethylamino)methyl]benzene: ^1H NMR (300 MHz, C_6D_6) δ 7.24−7.07 (m, 4 H, Ar H), 3.20 (s, 2 H, CH_2), 2.30 (s, 3 H, $ArCH_3$), 2.06 (s, 6 H, NCH_3); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 137.3, 137.2, 130.3, 129.9, 127.1, 125.6, 62.2 (CH_2N), 45.6 (NCH_3), 19.2 ($ArCH_3$). 4-Methyl-1-[(dimethylamino)methyl]benzene: ^1H NMR (300 MHz, $CDCl_3$) δ 7.21 (d, 2 H, J = 8.0 Hz), 7.14 (d, 2 H, J = 8.0 Hz), 3.40 (s, 2 H, CH_2), 2.36 (s, 3 H, $ArCH_3$), 2.25 (s, 6 H, NCH_3); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 136.4, 135.7, 129.1, 128.9, 64.1 (CH_2), 45.2 (NCH_3), 21.1 ($ArCH_3$).

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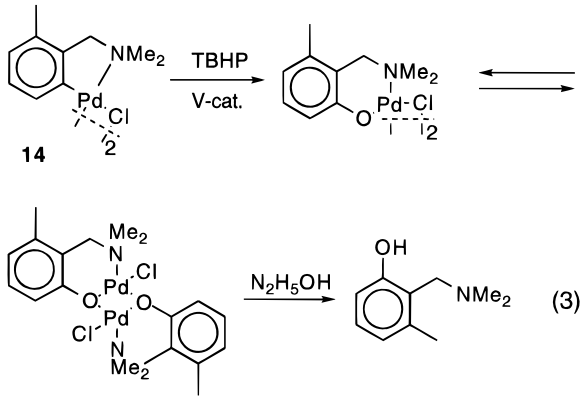
1-Chloro-3-methyl-2-[(dimethylamino)methyl]benzene. To a solution of 1,3-dichloro-2-[(dimethylamino)methyl]-benzene (34.7 g, 0.17 mol) in pentane (50 mL) was added 100 mL of a solution of *t*-BuLi (1.7 M in pentane, 0.17 mol) at −78 °C. While the mixture was warmed to room temperature slowly (not less than 30 min), a beige precipitate was formed. After it was stirred at room temperature overnight, the red solution was decanted. The solid residue was washed twice with 50 mL of pentane and dried *in vacuo*. The yield of beige {1-chloro-2-[(dimethylamino)methyl]-3-phenyl}lithium was 25.9 g (0.15 mol, 87%). To a solution of the latter (12.3 g, 70.2 mmol) in THF (20 mL) was added, while cooling with an ice bath, a solution of MeI (9.97 g, 70.3 mmol) in THF (20 mL). After the mixture was stirred at room temperature for 3 h, H_2O (20 mL) and Et_2O (100 mL) were added. The layers were separated, and the aqueous phase was extracted twice with 50 mL of Et_2O. The collected organic layers were dried on $MgSO_4$ and concentrated under reduced pressure. The oily residue was distilled *in vacuo* (bp 57 °C, 0.7 mmHg). The yield of colorless product was 11.9 g (64.9 mmol, 92%). ^{1}H NMR (**2**, 300 MHz, $CDCl_3$): δ 7.13−7.03 (m, 3 H, Ar H), 3.62 (s, 2 H, CH_2), 2.39 (s, 3 H, $ArCH_3$), 2.31 (s, 6 H, NCH_3).

Syntheses of Phenolic Derivatives. 2-[(Dimethylamino)-methyl]phenol, 6-methyl-2-[(dimethylamino)methyl]phenol, and 5-methyl-2-[(dimethylamino)methyl]phenol were prepared by performing a Mannich reaction on phenol or the corresponding cresols.[16]

1-Hydroxy-3-methyl-2-[(dimethylamino)methyl]benzene. Attempts to prepare this phenol *via* 1-hydroxy-3-methyl-2-benzoic acid failed. However, it was obtained in 80% yield by catalytic oxidation of arylpalladium chloride **14** (vide infra) and subsequent reductive removal of palladium (eq 3).[6]



To a solution of **14** (9.7 g, 16.7 mmol) in CH_2Cl_2 (500 mL) was added $VO(acac)_2$ (0.22 g, 0.83 mmol) and 10.9 mL of *tert*-butyl hydroperoxide (80% solution in di-*tert*-butyl peroxide, 87.5 mmol). After 10 min a slightly exothermic reaction started, upon which the solvent started to reflux. After it was stirred at room temperature for 2 days, the solution was concentrated to a volume of approximately 200 mL. To this solution was added with vigorous stirring 5.0 g of N_2H_5OH (0.10 mol). After the mixture was stirred at room temperature for 6 h, water (500 mL) was added. The layers were separated, and the aqueous phase was extracted twice with 250 mL of pentane. After drying on $MgSO_4$, filtration, and careful removal of the solvent under slightly reduced pressure a light yellow oil remained which contained 4.41 g of product (26.8 mmol, 80%) and 0.40 g of [(dimethylamino)methyl]benzene (2.7 mmol). The most convenient way to separate both compounds was to convert the phenol into insoluble sodium phenolate with NaH (*vide infra*), leaving [(dimethylamino)methyl]benzene in the pentane solution. ^{1}H NMR of 1-Hydroxy-3-methyl-2-[(dimethylamino)methyl]benzene: ^{1}H NMR (200 MHz, $CDCl_3$) δ 11.2 (bs, 1 H, OH), 7.05 (pseudo-t, 1 H, J = 7.8 Hz), 6.68 (d, 1 H, J = 8.0 Hz), 6.61 (d, 1 H, J = 7.6 Hz), 3.64 (s, 2 H, CH_2), 2.31 (s, 6 H, NCH_3), 2.22 (s, 3 H, $ArCH_3$); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 158.7 (CO), 136.2, 128.2, 121.0, 119.9, 114.3, 58.6 (CH_2), 44.5 (NCH_3), 19.7 ($ArCH_3$).

Syntheses of Naphthol Derivatives. 2-[(Dimethylamino)methyl]-1-naphthol was prepared by performing a Mannich reaction on 1-naphthol.[17] 2-[(Dimethylamino)methyl]-3-methyl-1-naphthol **(6a)** was prepared as recently described.[5a]

Synthesis of Sodium Phenolates and Naphtholates. A solution of the appropriate phenol (11 mmol) in pentane (40 mL) was added to a vigorously stirred suspension of NaH (10 mmol) in pentane (30 mL). After the mixture was stirred at room temperature for 30 min, the supernatant solution was decanted. The white solid was washed with two 50 mL portions of pentane and dried *in vacuo*. The yields were virtually quantitative for all compounds. For the preparation of the phenolate of 1-hydroxy-3-methyl-2-[(dimethylamino)-methyl]benzene a slightly modified procedure was used. After the mixture of phenol and NaH was stirred for 30 min, the solution was cooled to −18 °C. The crystals which separated from the solution were collected and dried *in vacuo*. The yield was 90%. **14**: ^{1}H NMR (300 MHz, CD_3OD) δ 6.88 (t, 1 H, J = 7.8 Hz), 6.53 (d, 1 H, J = 8.1 Hz), 6.42 (d, 1 H, J = 7.3 Hz), 3.59 (s, 2 H, CH_2), 2.28 (s, 6 H, NCH_3), 2.24 (s, 3 H, $ArCH_3$); ^{13}C NMR (75.5 MHz, CD_3OD) δ 163.3 (CO), 138.6, 128.9, 123.6, 119.7, 116.6, 57.3 (CH_2), 45.0 (NCH_3), 20.0 ($ArCH_3$). **16**: ^{1}H NMR (300 MHz, CD_3OD) δ 6.90 (d, 1 H, J = 7.3 Hz), 6.84 (d, 1 H, J = 7.3 Hz), 6.48 (t, 1 H, J = 7.4 Hz, H^4), 3.58 (s, 2 H, CH_2), 2.27 (s, 6 H, NCH_3), 2.16 (s, 3 H, $ArCH_3$).

Lithiation Reactions. The lithiation reactions of 4-methyl-1-[(dimethylamino)methyl]benzene,[18] 2,6-dichloro-1-[(dimethylamino)methyl]benzene, and 1-bromo-2-[(dimethylamino)methyl]-6-methylbenzene[15] were carried out using literature procedures.

Syntheses of Diarylzinc Compounds. Bis{2-[(dimethylamino)methyl]phenyl}zinc **(3)**,[19] bis{6-methyl-2-[(dimethylamino)methyl]phenyl]zinc **(4)**,[15] and bis[5-methyl-2-[(dimethylamino)methyl]phenyl]zinc **(5)** were prepared by reaction of the appropriate aryllithium compound with $^1/_2$ equiv of $ZnCl_2$ at −78 °C in THF. **5** was crystallized from hot hexane (91% yield). ^{1}H NMR (300 MHz, C_6D_6): δ 7.85 (s, 1 H, H^{ortho}), 7.14 (d, 1 H, J = 7.5 Hz), 7.05 (d, 1 H, J = 7.6 Hz), 3.31 (s, 2 H, CH_2), 2.40 (s, 3 H, $ArCH_3$), 1.96 (s, 6 H, NCH_3). ^{13}C NMR (75.5 MHz, C_6D_6): δ 156.9, 144.0, 140.7, 134.6, 126.9, 124.8, 67.4 (CH_2), 45.3 (NCH_3), 21.7 ($ArCH_3$). Anal. Calcd for $C_{20}H_{28}N_2Zn$: C, 66.39; H, 7.80; N, 7.74. Found: C, 65.33; H, 7.86; N, 7.20.

Bis{2-[(dimethylamino)methyl]-3-methylphenyl}-zinc (6). To magnesium (3.0 g, 0.12 mol), activated with 1,2-dibromoethane, in THF (40 mL) was added a solution of 1-chloro-3-methyl-2-[(dimethylamino)methyl]benzene (10.0 g, 54.5 mmol) in THF (20 mL). No temperature effect was observed during this addition. The resulting mixture was heated to reflux overnight with vigorous stirring. After it was cooled to room temperature, the dark solution was separated by centrifugation and THF was added to a total volume of 100 mL. The concentration was determined by titration with a solution of *s*-BuOH in *p*-xylene (0.1 M) using 1,10-phenanthroline as indicator.[20] The yield of Grignard reagent was 94% (50.7 mmol). A 90 mL portion (43.7 mmol) of this solution was added over a period of 20 min to a solution of $ZnCl_2$ (2.90 g, 21.3 mmol) in THF (20 mL) at 0 °C. After the grayish solution

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Table 1. Selected ^{1}H NMR Data for Diarylpalladium Compounds[a]

compd	CH_2[b]	NCH_3	$ArCH_3$
7	4.87 (12.9), 4.61 (12.5), 3.34 (12.9), 3.26 (12.5)	2.85, 2.78, 2.46, 2.32	
8	4.86 (12.9), 4.57 (12.4), 3.33 (12.9), 3.23 (12.4)	2.83, 2.78, 2.45, 2.31	1.94
9	4.66 (13.4), 4.63 (12.7), 3.58 (13.3), 3.26 (12.5)	2.85, 2.80, 2.46, 2.42	2.34
10	4.66 (13.4), 4.41 (12.8), 3.57 (13.4), 3.54 (12.8)	2.88, 2.80, 2.46, 2.44	2.33, 2.27
11	4.65 (13.4), 4.60 (12.4), 3.57 (13.4), 3.23 (12.4)	2.85, 2.81, 2.46, 2.44	2.30, 1.92
12	4.82 (12.1), 4.63 (12.8), 3.57 (12.8), 3.22 (12.2)	2.82, 2.79, 2.42, 2.31	2.26, 1.55

[a] All values are in δ relative to Me_4Si; $CDCl_3$ solvent at 25 °C. [b] All signals are doublets (part of AX pattern) unless otherwise stated. $^2J_{HH}$ values are given in parentheses in Hz.

was stirred for 1 h at room temperature, the solvent was removed *in vacuo*. The resulting white solid was extracted twice with 100 mL of hot toluene. The collected solutions were cooled to −18 °C, upon which white crystals separated that were isolated, washed with two 20 mL portions of cold toluene, and dried. The yield of **6** was 69%. **6**: ^{1}H NMR (300 MHz, C_6D_6) δ 7.93 (d, 1 H, J = 6.8 Hz, H^{ortho}), 7.32 (t, 1 H, J = 7.2 Hz), 7.14 (d, 1 H, J = 7.4 Hz), 3.35 (s, 2 H, CH_2), 2.21 (s, 3 H, $ArCH_3$), 1.96 (s, 6 H, NCH_3); ^{13}C NMR (75.5 MHz, C_6D_6) δ 156.5, 144.6, 137.5, 132.1, 128.1, 125.9, 64.5 (CH_2), 45.7 (NCH_3), 20.0 ($ArCH_3$). Anal. Calcd for $C_{20}H_{28}N_2Zn$: C, 66.39; H, 7.80; N, 7.74. Found: C, 64.53; H, 7.78; N, 7.35.

Cyclometalated Derivatives of [(Dimethylamino)-methyl]benzene: [3-Me-$C_6H_3CH_2NMe_2$-2)PdCl]$_2$ (14). To a solution of Li_2PdCl_4 (36.0 mmol in 200 mL of MeOH) was added a solution of 2-methyl-1-[(dimethylamino)methyl]benzene (5.36 g, 36 mmol) and NaOAc (2.95 g, 36.0 mmol) in MeOH (50 mL). After the mixture was stirred at room temperature overnight, the yellow precipitate was collected and washed successively with MeOH (50 mL) and Et_2O (100 mL). The product was dried *in vacuo*. The yield of yellow **14** was 9.7 g (16.7 mmol, 93%). Crystals were obtained by slow distillation of Et_2O into a solution of **14** in CH_2Cl_2. **14**: ^{1}H NMR (300 MHz, $CDCl_3$, mixture of isomers) δ 7.10−6.90 (m, 1 H, Ar H), 6.78−6.75 (m, 2 H, Ar H), 3.92 (s, 2 H, CH_2), 2.88 and 2.86 (2s, 6 H, NCH_3), 2.17 (s, 3 H, $ArCH_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 144.9, 131.5, 131.2, 130.7, 126.3, 125.4, 71.5 and 71.3 (CH_2), 53.2 and 52.9 (NCH_3), 20.7 ($ArCH_3$). Anal. Calcd for $C_{20}H_{28}Cl_2N_2Pd_2$: C, 41.40; H, 4.86; N, 4.83. Found: C, 41.33; H, 4.89; N, 4.77.

{5-Methyl-2-[(dimethylamino)methyl]-1-phenyl}palladium Chloride Dimer (15). This compound was prepared according to the procedure described for {3-methyl-2-[(dimethylamino)methyl]phenyl}palladium chloride dimer **14** (*vide supra*) in 86% yield. **15**: ^{1}H NMR (300 MHz, $CDCl_3$, mixture of isomers) δ 6.96 (d, 1 H, J = 16.7 Hz), 6.74 (m, 2 H), 3.87 (s, 2 H, CH_2), 2.82 and 2.80 (2s, 6 H, NCH_3), 2.24 and 2.23 (2s, 3 H, $ArCH_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$, mixture of isomers) δ 143.9, 143.7, 142.9, 134.7, 133.9, 133.4, 125.5, 121.2, 73.1, and 73.0 (CH_2), 52.8 and 52.5 (NCH_3), 21.4 ($ArCH_3$). Anal. Calcd for $C_{20}H_{28}N_2Pd_2Cl_2$: C, 41.41; H, 4.86; N, 4.83. Found: C, 41.29; H, 4.82; N, 4.86.

{6-Methyl-2-[(dimethylamino)methyl]phenyl}palladium Bromide Dimer (16). A solution of 2-bromo-3-methyl-1-[(dimethylamino)methyl]benzene[21] (2.0 g, 8.8 mmol) in acetone (10 mL) was added to a suspension of $Pd(dba)_2$ (5.0 g, 8.7 mmol) in acetone (50 mL). The mixture was stirred at 50 °C for 1 h. The yellow-green solid was isolated by centrifugation, washed with Et_2O (100 mL), and dried *in vacuo*. Extraction with CH_2Cl_2 (100 mL) and removal of the solvent under reduced pressure yielded 2.62 g (7.8 mmol, 93%) of bright yellow **16**. Crystals were obtained by slow distillation of Et_2O into a solution of **16** in CH_2Cl_2. **16**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.85 (t, 1 H, J = 7.3 Hz, H^4), 6.74−6.70 (m, 2 H), 4.11 (s, 2 H, CH_2), 2.71 (s, 6 H, NCH_3), 2.55 (s, 3 H, $ArCH_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 146.5, 145.0, 142.9, 127.6, 124.6, 119.4, 73.9 (CH_2), 52.8 (NCH_3), 26.5 ($ArCH_3$).

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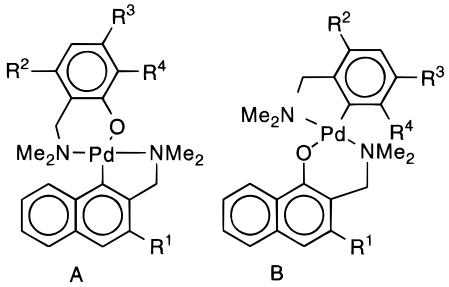
Syntheses of Diarylpalladium Compounds 7−12 (Cf. Scheme 1). Synthesis of 8. A solution of Li(2-$C_6H_3CH_2$-NMe_2-1-Me-4) (1.29 mmol) in THF (10 mL) was added over a period of 10 min to a yellow solution of the arylpalladium compound **2** (1.29 mmol) in THF (30 mL) at −78 °C. The clear, colorless reaction mixture was warmed to room temperature and was stirred for another 30 min. The solvent was removed under reduced pressure, Et_2O (40 mL) was added, and the suspension was stirred for 30 min. The solvent was removed by decantation. The residue was washed with three portions of Et_2O (10 mL) and separated from metallic palladium by extraction with benzene (30 mL). The solvent was removed *in vacuo*, leaving a white solid. Compound **8** (0.40 g, 0.91 mmol, 71%) was crystallized from benzene and pentane. See Table 1 for selected ^{1}H NMR data. We have been unable to get good elementary analyses for this compound. ^{1}H NMR spectra and full NMR data have been supplied as Supporting Information.

Syntheses of 7 and 9−12. A solution of the appropriate diarylzinc compound (1.0 mmol) in benzene (10 mL) was added in one portion at room temperature to a solution of **1** or **2** (1.0 mmol) in benzene (30 mL). After the colorless solution was stirred for 5 min, the solvent was removed under reduced pressure. The white residue was washed with two portions of Et_2O (10 mL), which were removed by decantation after stirring the suspension for 10 min. Drying *in vacuo* gave the colorless compounds **7** (90%), **9** (97%), **10** (95%), **11** (93%), and **12** (87%). All compounds were crystallized from benzene and pentane. In the synthesis of **7**, bis(1-naphthyl)palladium, which had formed as a byproduct, was extracted with two portions of 10 mL of Et_2O. See Table 1 for selected ^{1}H NMR data. Full NMR data have been supplied as Supporting Information. Anal. Calcd for **9**, $C_{23}H_{28}N_2Pd$: C, 62.94; H, 6.43; N, 6.38. Found: C, 63.06; H, 6.43; N, 6.40. Calcd for **10**, $C_{36}H_{42}N_2Pd$: C, 67.87; H, 6.79; N, 5.31. Found: C, 67.88; H, 6.92; N, 5.36. Calcd for **11**, $C_{36}H_{42}N_2Pd$: C, 67.87; H, 6.79; N, 5.31. Found: C, 67.83; H, 6.89; N, 5.31. Calcd for **12**, $C_{24}H_{30}N_2Pd$: C, 63.64; H, 6.68; N, 6.18. Found: C, 62.88; H, 6.70; N, 5.99. We have been unable to get reliable elementary analyses for **7**. ^{1}H NMR spectra and full NMR data have been supplied as Supporting Information.

Syntheses of (Aryl)(aryloxide)palladium Compounds 7′−12′ and 7″−12″ (Cf. Scheme 2). A solution of the appropriate sodium phenoxide or sodium naphthoxide (1.0 mmol) in THF (10 mL) was added to a solution of one of the palladium compounds **1**, **2**, **13**, **14**, **15**, and **16** in THF (20 mL). After the mixture was stirred at room temperature for 3 h, the solvent was removed *in vacuo*. Pentane (10 mL) was added, and the mixture was stirred for 30 min. Pentane was decanted and the residue extracted with CH_2Cl_2 (20 mL). After removal of the solvent under reduced pressure a yellow product remained. The yields are over 95% in all cases. Crystallization was achieved by diffusion of Et_2O into a concentrated solution of product in CH_2Cl_2. All compounds are moderately soluble in Et_2O. See Table 2 for selected ^{1}H NMR data. Full NMR data have been supplied as Supporting Information. Elemental Analyses were obtained for a number of key compounds. Anal. Calcd for **7″**, $C_{22}H_{26}N_2OPd$: C, 59.93; H, 5.94; N, 6.35. Found: C, 59.86; H, 6.09; N, 6.42. Calcd for **9″**, $C_{23}H_{28}N_2OPd$: C, 60.73; H, 6.20; N, 6.16. Found: C, 60.56;

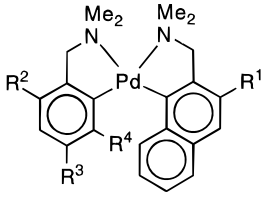
Table 2. Selected ^{1}H NMR Data for (Aryl)(aryloxy)palladium Compounds[a,b]



compd	A/B	R^1	R^2	R^3	R^4	CH_2	NCH_3	$ArCH_3$
7″	A	H	H	H	H	4.33, 3.98[c]	2.61, 2.52	
8″	A	H	H	Me	H	4.30, 3.94	2.60, 2.49	2.29
9″	A	Me	H	H	H	4.3−3.5[c]	2.62, 2.45	2.39
10″	A	Me	Me	H	H	4.32, 4.03	2.67, 2.55	2.48, 2.33
11″	A	Me	H	Me	H	4.5−3.6[c,d]	2.65, 2.47	2.44, 2.34
12″	A	Me	H	H	Me	5.5−3.5[c]	2.71, 2.51	2.47, 2.39
7′	B	H	H	H	H	3.99, 3.58	2.91, 2.82	
8′	B	H	H	Me	H	3.95, 3.58	2.90, 2.82	2.32
9′	B	Me	H	H	H	3.98, 3.64	2.92, 2.86	2.44
10′	B	Me	Me	H	H	4.00, 3.67	2.96, 2.85	2.46, 2.26
11′	B	Me	H	Me	H	3.95, 3.67	2.92, 2.89	2.47
12′	B	Me	H	H	Me	4.18, 4.07	2.66, 2.61	2.58, 2.41

[a] All values are in δ relative to Me_4Si; $CDCl_3$ solvent at 25 °C. [b] All signals are singlets unless otherwise stated. [c] Broad signals. [d] At 220 K these protons show AX patterns: 5.14 (1 H, J = 13.5 Hz), 4.89 (1 H, J = 13.9 Hz), 3.66 (1 H, J = 14.0 Hz), 2.87 (1 H, J = 13.7 Hz).

Table 3. Results of the Oxidation of Diarylpalladium Compounds



compd	R^1	R^2	R^3	R^4	rel amt of naphthyl oxidn	rel amt of phenyl oxidn	total yield (%)
7	H	H	H	H	80	20	85
8	H	H	Me	H	90	10	83
9	Me	H	H	H	50	50	89
10	Me	Me	H	H	80	20	91
11	Me	H	Me	H	82	18	93
12	Me	H	H	Me	75	25	87

H, 6.24; N, 6.10. Calcd for **11″**, $C_{24}H_{30}N_2OPd$: C, 61.47; H, 6.45; N, 5.97. Found: C, 61.34; H, 6.48; N, 6.03. Calcd for **7′**, $C_{22}H_{26}N_2OPd$: C, 59.93; H, 5.94; N, 6.35. Found: C, 59.81; H, 6.07; N, 6.30. Calcd for **9′**, $C_{23}H_{28}N_2OPd$: C, 60.73; H, 6.20; N, 6.16. Found: C, 60.82; H, 6.28; N, 6.12.

Oxidation Reactions. The oxidations were carried out by adding 1 mmol of TBHP (as an 80% solution in di-*tert*-butyl peroxide) to a solution of a diarylpalladium compound (1 mmol) in CH_2Cl_2 (10 mL). The reaction was performed at room temperature, and the mixture was stirred for 3 h. After that time, the solvent was removed *in vacuo*.[22] The residue was washed with two 10 mL portions of pentane and dried. Analysis was carried out by recording the ^{1}H as well as the ^{13}C NMR spectrum of the residue. Furthermore, the residue was reacted with N_2H_5OH, after which the organic fragments were identified by NMR spectroscopy. The results are summarized in Table 3.

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Supporting Information Available: Text giving full NMR data for compounds **7**−**12**, **7′**−**12′**, and **7″**−**12″** and figures giving ^{1}H NMR spectra of compounds **7** and **8** (6 pages). Ordering information is given on any current masthead page.

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(22) The oxidations may also be carried out in benzene or *tert*-butyl alcohol solution. When *tert*-butyl alcohol is used, the reaction temperature should be increased to 40 °C. Reaction times may be shortened to 30 min by adding 5 mol % (based on oxidant) of $VO(acac)_2$ or $[RhCl(cod)]_2$ as catalyst. The oxidation ratios is given in Table 3 are independent of the reaction conditions used.