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Mechanisms of 1,1-Reductive Elimination from Palladium: Elimination of Ethane from Dimethylpalladium(II) and Trimethylpalladium(IV)

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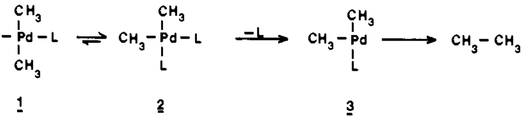
Abstract: The energies and entropies of activation for the 1,1-reductive elimination of ethane from *cis*-bis(diphenylmethylphosphine)dimethylpalladium(II) (**2a**) in polar and nonpolar solvents were determined. The rates of elimination are slower in polar solvents such as Me_2SO, acetone, and acetonitrile than in nonpolar solvents such as benzene. The energies of activation in nonpolar solvents are very close (25 kcal/mol) to the calculated values (extended HMO). Lower energies of activation (6–10 kcal/mol) but high negative entropies of activation (~45 eu) in polar solvents are consistent with an elimination that produced a coordinatively unsaturated palladium(0) complex and a late transition state having the characteristics of the product, such that solvent coordinates during the transition state. Reaction of **2a** or the corresponding bis(triphenylphosphine)dimethylpalladium(II) complex **2b** with methyl iodide yields ethane and the *trans*-bis(phosphine)iodomethylpalladium(II) complexes (**10a,b**). The second-order reaction proceeds through a rate-determining oxidative addition of methyl iodide to **2a,b**, yielding the bis(phosphine)iodotrimethylpalladium(IV) intermediate, followed by a rapid elimination. In polar solvents, the rates of these reactions are faster than the 1,1-reductive eliminations from **2a,b** mostly because of the lower entropies of activation in the oxidative addition step. In nonpolar solvents, the rates are comparable. The reaction of **2a,b** with CD_3I gave both C_2H_6 and $C_2H_3D_3$, the ratios of these isomers in the reaction of **2a** being most consistent with the trans oxidative addition reaction followed by statistical reductive elimination from adjacent methyls.

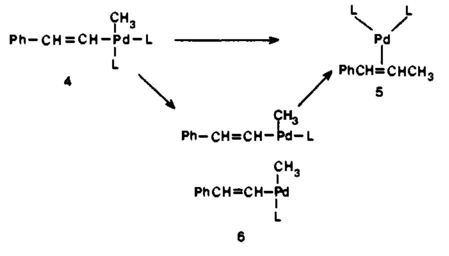
Examination of the requirements for 1,1-reductive elimination of organic partners from palladium to generate coupled products has shown that there are several available mechanistic pathways,[1,2] depending on the donor or acceptor strengths of the organic partners and the ligands, the ability of the complex to dissociate a ligand, and the stability of the lower valent palladium complex product.[3] The 1,1-reductive elimination of ethane from bis(phosphine)dimethylpalladium(II) (**1**, **2**) takes place only from the cis complex, isomerization from trans to cis via an associative mechanism being required if the starting dimethylpalladium complex is trans.[1] The coupling takes place by the prior dissociation of a ligand, followed by the intramolecular elimination.[1] Extended Hückel calculations reveal that the elimination proceeds either from a T- or a Y-shaped intermediate (**3**) bearing methyl groups in the closest positions.



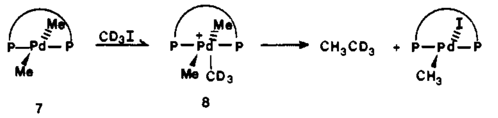
1 **2** **3**

L = $PMePh_2$, PPh_3

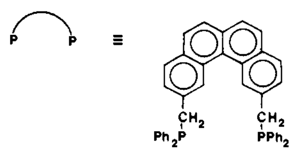
The elimination of methyl and vinyl groups from palladium(II) also requires the cis complex **4**, but prior dissociation of a phosphine ligand is not required, apparently because the palladium product, a relatively stable bis(phosphine)olefinpalladium(0) complex (**5**), provides a low-energy pathway for 1,1-reductive elimination from the four-coordinate reactant.[2] Nevertheless, elimination from a three-coordinate complex (**6**) is a competing pathway, particularly toward the end of the reaction when the demand for ligand by the palladium(0) product becomes critical.[2]



A dimethylpalladium(II) complex containing a phosphine ligand that bridges trans coordination sites, dimethyl(TRANSPHOS)palladium(II) (**7**), and thus does not allow the methyl groups to gain adjacent positions, does not undergo reductive elimination of ethane, even at 100 °C in a polar solvent. Addition of methyl iodide to a solution of the TRANSPHOS complex causes the immediate reductive elimination of ethane, even at 25 °C, a temperature at which the cis palladium(II) complexes are stable. Further, when trideuteriomethyl iodide is added to the TRANSPHOS complex, only trideuterioethane is eliminated, implicating a trimethylpalladium(IV) complex (**8**) as an intermediate in the elimination reaction. This rapid rate of reductive elimination involving the palladium(IV) intermediate provides an explanation for the observation that the rates of reductive elimination from palladium(II) complexes are often slower than the rates of any of the individual steps in the catalytic coupling reactions of alkyl halides and organometals.



7 **8**



In order to understand further the requirements of reductive elimination and coupling reactions catalyzed by palladium, we compare, in this paper, the reductive elimination of ethane from palladium(II) and palladium(IV) in polar and nonpolar solvents and report the energies and entropies of activation for these reactions.

Results and Discussion

Since the trans dimethylpalladium complexes isomerize rapidly to the cis complexes, particularly in polar solvents, the reductive elimination from the cis complex **2a** (L = $PMePh_2$) was observed. For comparison, the reductive elimination of ethane from the reaction of **2a,b** (L = $PMePh_2$ and PPh_3) in the presence of methyl iodide was also followed. The synthesis of these complexes has been described.[1] The reaction kinetics were obtained in different solvents over a range of temperatures and were followed by ob-

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Table I. 1,1-Reductive Elimination of Ethane from *cis*-Bis(diphenylmethylphosphine)dimethylpalladium(II)

solvent	$10^4 K$, s^{-1} (60 °C)[a]	E_a, kcal/mol	$\Delta S^\ddagger$, eu
$Me_2SO\text{-}d_6$	1.7[b]	6.00 ± 0.7	−61 ± 5
$Me_2CO\text{-}d_6$	1.6	10.6 ± 1	−46 ± 3
CD_3CN	2.7	10.5 ± 1	−45 ± 3
$C_6D_5CD_3$	12	27.4 ± 2	8.2 ± 4
C_6D_6	10[c]	25.0 ± 2	0.5 ± 4

[a] Estimated to be ±5%, except for runs in $Me_2SO\text{-}d_6$ and $Me_2CO\text{-}d_6$. Rate constants in $Me_2SO\text{-}d_6$ and $Me_2CO\text{-}d_6$ taken from the first half of the decomposition since nonlinear plots were obtained at the end of the run; errors are estimated to be <±10%. Added diphenylmethylphosphine (0.02–0.1 M) retarded the rate of reductive elimination. [b] Due to an error in the temperature calibration of the NMR probe, the rate constant, 9.625×10^{-5}, reported in ref 1 at 60 °C in $Me_2SO\text{-}d_6$, was, in fact, measured at 54 °C. [c] We had reported[1] that dissociation of phosphine from deuteriobenzene solutions of *cis*-1 could not be observed by NMR (at ambient probe temperatures) and that no reductive elimination took place under these conditions. At 60 °C the reductive elimination takes place rapidly with the rate constant listed, but the presence of dissociated phosphine could not be established unequivocally by ^{31}P NMR.

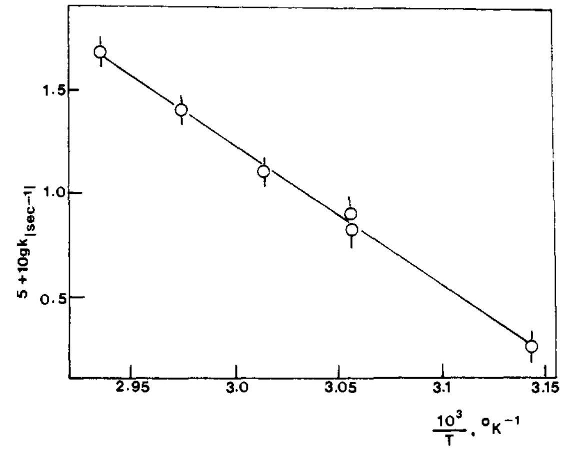


Figure 1. Temperature dependence of the rate constant of thermal decomposition of *cis*-$(PPh_2Me)_2PdMe_2$ (0.02 M) in $Me_2SO\text{-}d_6$.

serving the disappearance of the methyl bound to palladium in the ^1H NMR.

1,1-Reductive Elimination from *cis*-Dimethylpalladium(II). The chemical shifts and coupling constants for both palladium and phosphorus methyls in various solvents show that in the aromatic solvents the palladium methyl is shifted downfield. Because of the complications due to the involvement of the phosphorus methyl as the reaction proceeds,[1] the rate constants were taken from the first half of the reaction. The deviation from linearity toward the end of the reaction was most pronounced in dimethyl sulfoxide and acetone, but linear plots were obtained in the remaining solvents, acetonitrile, toluene, and benzene. The rates of reductive elimination of ethane are faster by almost an order of magnitude in the aromatic solvents (Table I).

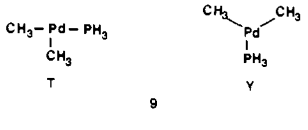
The dependency of the rates of disappearance of **2a** with temperature, over at least three temperatures for each solvent, gave a linear Arrhenius plot. The linearity of the Arrhenius plot over a temperature range from 75 to 50 °C (five temperatures) in $Me_2SO\text{-}d_6$ is shown in Figure 1. From the empirical activation energies, the thermodynamic entropies of activation, $\Delta S^\ddagger$, were calculated. The energies of activation (Table I) for the reductive eliminations in the nonpolar aromatic solvents correspond to those calculated (25 kcal/mol)[3] for the *cis*-dimethylphosphine-palladium(II) complex in either the T or Y geometry (**9**). The

Table II. Reaction of Methyl Iodide with *cis*-Bis(diphenylmethylphosphine)dimethylpalladium(II) (**2a**)

solvent	K, M^{-1} s^{-1} [a] (20 °C)	E_a, kcal/mol	$\Delta S^\ddagger$, eu
$Me_2SO\text{-}d_6$	2.4×10^{-3}	16.0 (±2)	−17.0 (±4)
$Me_2CO\text{-}d_6$	4.9×10^{-4}	16.2 (±1)	−20.3 (±3)
CD_3CN	2.7×10^{-3}	16.8 (±0.8)	−14.7 (±4)
$CDCl_3$[b]	2.7×10^{-4}	14.5 (±0.5)	−28.0 (±3)
$C_6D_5CD_3$	1.56×10^{-5}	25.0 (±1)	2.9 (±4)
C_6D_6	2.6×10^{-5}	21.5 (±1)	−8.0 (±3)

[a] Initial [**2a**], 0.02 M. $[CH_3I]$ varied from 0.1 to 3.0 M. Estimated to be ±5%. [b] Because of the relatively high concentrations of methyl iodide (3.0 M), $CDCl_3$ did not undergo oxidative addition to **2a**.

lower energies of activation and slower rates for those eliminations in polar coordinating solvents are a reflection of the large negative entropies of activation. These large negative values are consistent with an elimination reaction that produces a coordinatively unsaturated palladium(0) complex, $L_2Pd(0)$, and a late transition state having some of the characteristics of the product. Thus, an ordering of coordinating solvent by palladium appears to be taking place as it proceeds to the zero-valent complex. Since this reaction takes place by prior dissociation of phosphine,[1] the observed activation energy is the sum of an endothermic ligand dissociation and the elimination of ethane. Coordination of solvent to the product to give L_2PdS_n (S = Me_2SO, acetone, acetonitrile) lowers the energy of the b_2 orbital[3] in the product and thus the activation energy for the reductive elimination.



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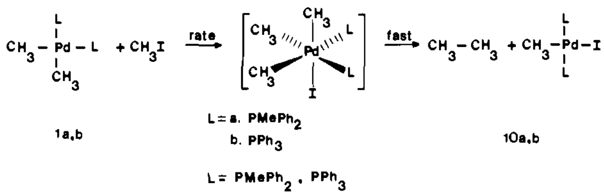
Reductive Elimination from Pd(IV). The reaction of methyl iodide with *cis*-bis(phosphine)dimethylpalladium(II) complexes (**2a**,**b**) in solvents of different polarity gave ethane and the *trans*-bis(phosphine)iodomethylpalladium(II) complexes (**10a**,**b**). The reaction could be carried out with convenient reaction times at 20 °C, and the course of the reaction was followed by monitoring the disappearance of the palladium-methyl signal as the reaction progressed. The reaction was carried out at various reaction temperatures with excess methyl iodide. Under these conditions the reaction followed pseudo-first-order kinetics; the observed rate constants were proportional to the concentration of methyl iodide. Thus, the expected rate law for a second-order reaction, rate = $k_2[\mathbf{2}][CH_3I]$, was established.

The chemical shifts of the palladium methyl both in the dimethylpalladium(II) complex **2a** and in the product methylpalladium iodide **10a** in toluene and benzene depend on the concentration of the methyl iodide (see Experimental Section). The upfield shift with increasingly greater methyl iodide concentrations indicates a molecular association, although the chemical shift of the phosphorus methyl is not affected.

The rate constants (Table II, Figure 2) are larger than those observed for the first-order reductive elimination of ethane from the *cis*-dimethylpalladium(II) complex **2a** in the same solvents. The rates for the reaction of **2a** with methyl iodide in the polar solvents are 3 (acetone) to 14 (Me_2SO) times faster at 20 °C than the rates of reductive elimination of ethane from palladium(II) at 60 °C. This represents a rate approximately 4×10^2 faster for the reaction of **2a** with methyl iodide at the same temperature in Me_2SO than for the first-order decompositions in the same solvent at the same temperature.

In nonpolar solvents, at 60 °C, the reductive elimination of ethane from **2a** is 40–80 times faster than the reaction of **2a** with methyl iodide (1.0 M) at 20 °C. Thus, these two reactions in nonpolar solvents have comparable rates at the same temperature (60 °C).

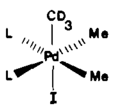
The second-order rate is consistent either with a rate-determining oxidative addition of methyl iodide to give the palladium(IV) intermediate followed by a fast 1,1-reductive elimination reaction or a reversible oxidative addition reaction followed by a rate-determining reductive elimination reaction. Since the intermediate palladium(IV) complex **11** cannot be observed by ^1H NMR during the course of the reaction, any preequilibrium constant must be small.



1a,b **10a,b**

The energies of activation (Table II, Figure 2) at least in the polar solvents do not show appreciable differences. Both the rates of the reaction and the entropies of activation are quite sensitive to the solvent, much faster rates and larger negative entropies being observed in polar media. This behavior is characteristic of oxidative addition reactions of methyl iodide to other transition metals. The effect of solvent on the rate of addition of methyl iodide to 2,2′-bipyridyldiphenylplatinum(II) has been attributed to a polar transition state characteristic of an S_N2 reaction.[4] Large negative entropies of activation are typical of oxidative addition reactions[5] as typified by the reaction of methyl iodide with (bpy)$PtPh_2$.[6] In these reactions, the solvent effect on the rate of oxidative addition is dominated by the entropy of activation term. The platinum(IV) product does not undergo reductive elimination readily, however, and can be isolated. The addition of an alkyl halide to diphosphinediorganoplatinum(II) complexes gives the triorganoplatinum(IV) complex that can be isolated, but these complexes then can be made to undergo a thermal reductive elimination of two of the organic partners.[7-12] The analogous triorganopalladium(IV) complexes, however, are too unstable and have not been isolated, the reaction of methyl iodide with (1,2-bis(diphenylphosphino)ethane)dimethylpalladium rapidly giving ethane.[13]

When the bis(phosphine)dimethylpalladium(II) complexes **2a** and **2b** were allowed to react with trideuteriomethyl iodide, both ethane and trideuterioethane were obtained along with the bis(phosphine)methylpalladium iodide (Table III). Several different geometries for the intermediate palladium(IV) can be written.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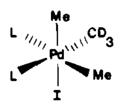
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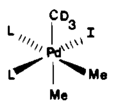
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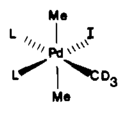
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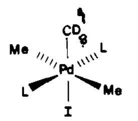
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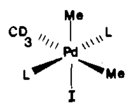
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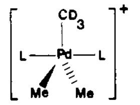
G

Only a complex containing equivalent and mutually adjacent methyl groups (in the absence of secondary isotope effects) could be expected to give a ratio of $[C_2H_6]/[C_2H_3D_3]$ of 0.5, and only a cationic complex such as G meets these requirements exactly.

The oxidative addition of methyl iodide to *cis*-dimethylbis(dimethylphenylphosphine)platinum(II) proceeds trans to give the *fac*-trimethylplatinum(IV) complex.[9,11,14] Isomerization of these appropriately labeled deuteriomethyl complexes does not take place at ambient temperatures (33 °C) but does occur slowly at 68 °C.[11] Pyrolysis of the labeled *fac*-trimethyl complexes at 120 °C gives the expected statistical ratio of ethane products resulting from complete intramolecular scrambling.

Table III. Composition of Ethane Evolved from the Reaction of CD_3I with Dimethylpalladium(II) Complexes 2a and 2b

complex	solvent	concentrations 2, M	 $[CD_3I]/[2]$	$C_2H_6/C_2H_3D_3$ (±5%)
2a	Me_2SO	6×10^{-2}	20	0.61
	C_6H_6	6×10^{-2}	20	0.69
2b	$CHCl_3$	6×10^{-2}	50	1.4
	C_6H_6	3×10^{-2}	30	0.93
(DIPHOS)$PdMe_2$	Me_2SO	2×10^{-2}	40	0.51

Analogously, oxidative addition of trideuteriomethyl iodide to complexes **2a** and **2b** would be expected to proceed to give the trans addition product A. Scrambling to B (the rearrangement observed in the analogous platinum compound)[11] would not be expected to take place at these lower temperatures although this rearrangement reaction is not amenable to study with palladium under the present reaction conditions.

Thus, in the absence of trans effects, complexes A and B would give the 0.5 ratio, while D and F would provide a ratio of 1 and only trideuterioethane would be generated by D and E. This assumes only adjacent methyl groups will undergo 1,1-reductive elimination in these palladium(IV) complexes, a requirement that has been demonstrated[1] in a rigid (TRANSPHOS)trimethylpalladium complex **8**, analagous to E.

When the ligands are held cis, as they are in (DIPHOS)dimethylpalladium, the oxidative addition of CD_3I could give any of the four complexes analogous to A–D, but the 0.51 ethane ratio could only be obtained from complex geometries A (expected) and B. The oxidative addition of methyl iodide to bipyridinediarylplatinum complexes gives a stable palladium(IV) complex.

These results are reasonably consistent with an oxidative addition of trideuteriomethyl iodide to **2a**, both in polar and nonpolar solvents, to give A, from which the reductive elimination of ethane takes place rapidly. The ethane ratios obtained from the oxidative addition of trideuteriomethyl iodide **2b**, however, are more consistent with structures C and F (C_6D_6) or mixtures of C, F, D, and E ($CDCl_3$).

Conclusions

Of the several possible 1,1-reductive elimination reaction pathways of organic groups from palladium, the reaction takes place only with the adjacent organic partners. From palladium(II) complexes, isomerization to the cis isomer must take place if the initially formed diorganopalladium species is trans.[1,2] Prior dissociation of a ligand from the cis complex to give a tricoordinate "Y" or "T"[3] shape complex may be a requirement for elimination, depending on the structure and particularly the coordination number of the palladium(0) complex first formed.

In eliminations from L_2PdR_2, the better the σ-donor capability of the leaving group and the weaker the donor trans to the leaving group, the more readily the 1,1-reductive elimination occurs.[3] Although the activation energies for these reductive elimination reactions are lower in more polar solvents, the attending large negative entropies of activation result in slower rates than in nonpolar solvents. Thus, in a polar solvent, the activation energy may be lowered because of the absence of the second phosphine ligand or its replacement by a polar solvent.

Strong donor ligands trans to the leaving group retard reductive elimination yet at the same time enhance the rate of oxidative addition by increasing the electron density on palladium. Thus, a more facile pathway for reductive elimination, particularly in the catalytic coupling reactions of organometals and organohalides

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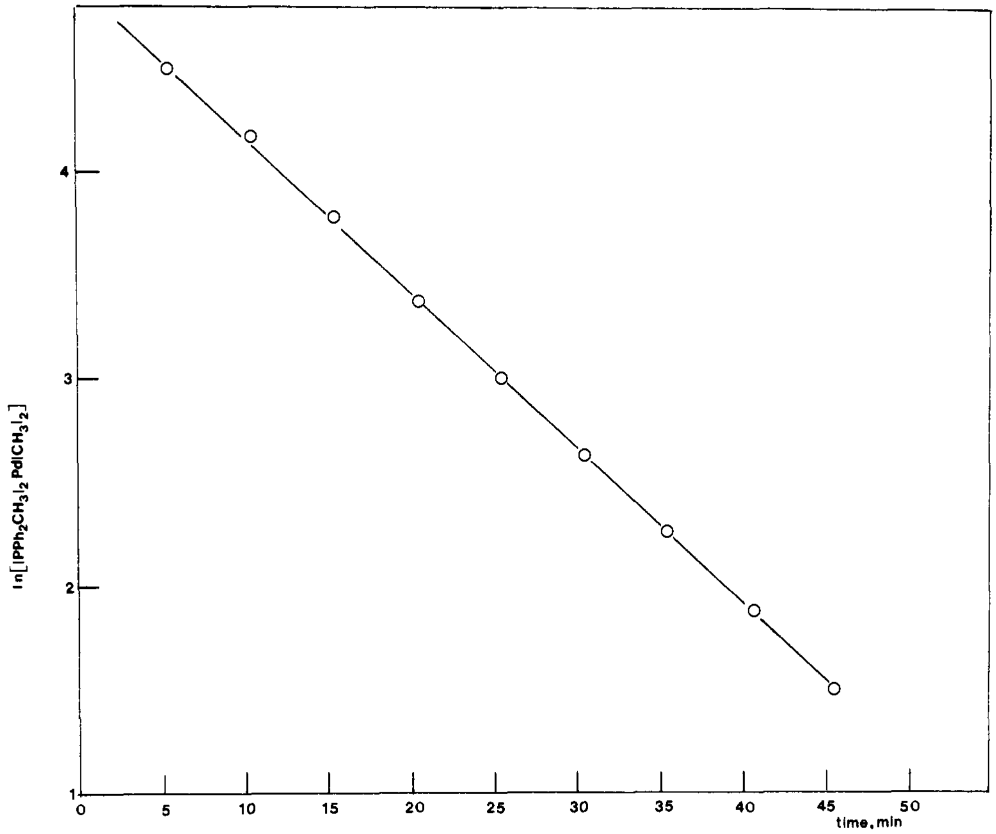

Figure 2. Rate of reaction of **2a** with methyl iodide in Me_2CO-d_6.

catalyzed by palladium (where the organo halide is present in excess with respect to palladium throughout the course of the reaction) may be through a palladium(IV) intermediate. In many catalytic reactions, the overall coupling rate, and thus every individual step in the catalytic cycle, is faster than the rate of the 1,1-reductive elimination from the diorganopalladium(II) complex. In polar solvents, the rates of the oxidative addition reductive elimination sequence involving dimethylpalladium(II) → iodotrimethylpalladium(IV) → iodomethylpalladium(II) is faster than the reductive elimination of ethane from dimethylpalladium(II), mostly because of the less negative entropies of activation for the oxidative addition step in the former sequence. In nonpolar solvents, these two pathways have competitive rates since both the activation energies and entropies for the two pathways are similar.

Experimental Section

Reactions were routinely performed under an argon atmosphere by using either Schlenk techniques or a drybox, and all solvents were purified immediately before use. Proton NMR spectra were determined on a JEOL FX-100 spectrometer. Phosphorus-31 spectra were recorded on a Nicolet NT-150. The JEOL FX-100 and Nicolet NT-150 instruments were equipped with a variable-temperature probe which allowed kinetic studies to be carried out at a temperature of choice without interrupting the reaction in order to record spectra. Samples were run in Me_2SO-d_6, Me_2CO-d_6, CD_3CN, $CDCl_3$, C_6D_6, or $C_6D_5CD_3$, as indicated. The known ^1H NMR δ values, relative to tetramethylsilane (δ 0), for residual protons in the deuterated solvents were used as a reference in determining the ^1H NMR δ values listed. Tetramethylsilane was omitted from the samples as an internal reference since it interfered with the palladium-methyl signal. Phosphorus-31 spectra are listed in δ relative to external 85% phosphoric acid.

Palladium Complexes. The dimethylpalladium complexes were synthesized as previously described.[1] The key features of the ^1H NMR spectra of these complexes are listed in Table IV (supplemental material).

Kinetic Runs. All solvents were dried and distilled prior to use. All samples were dried at reduced pressure (0.5 μmHg) for 16 h and dissolved under an argon atmosphere immediately before placing the sample in the probe. Experiments were performed by varying temperature, time intervals, and solvent system to establish the conditions at which the reaction could be closely followed on the JEOL FX-100 NMR. The variable-temperature probe was calibrated prior to each run by using a platinum resistance thermometer. The reductive elimination reactions were monitored by the disappearance of Pd-CH_3 resonances.

For the kinetics of the unimolecular reductive elimination of ethane from *cis*-bis(diphenylmethylphosphine)dimethylpalladium(II) (**2a**) (Table I), samples were made up with ~0.5 mL of the desired solvent, 0.02 M in **2a**. A concentration of 0.01 M also made up for the kinetic runs in Me_2SO-d_6 at 60 °C. Kinetics of the elimination were measured at the following temperatures for the various solvents: Me_2SO-d_6, 75, 70, 65, 60, 55, and 50 °C; Me_2CO-d_6, 55, 45, and 35 °C; CD_3CN, 65, 55, and 45 °C; $C_6D_5CD_3$, 70, 65, and 55 °C; C_6D_6, 70, 65, and 50 °C.

The second-order kinetics for the reaction of **2a** with methyl iodide (Table II) were measured with ~0.5 mL of the desired solvent, 0.02 M in **2a**. The solution was cooled down to a temperature above the freezing point of the mixture, but at a temperature such that the complex did not precipitate. Methyl iodide was added, and the mixture was rapidly warmed to the desired reaction temperature. The amount of methyl iodide added and the temperatures at which the reactions were run for the different solvents were the following: Me_2SO-d_6, 0.1 M MeI at 30, 25, and 20 °C, 0.3 M MeI at 20 °C; Me_2CO-d_6, 1 M MeI at 30, 20, and 10 °C, 0.3 M MeI at 20 °C; CD_3CN, 0.3 M MeI at 30, 20, and 10 °C, 1.0 M MeI at 20 °C; $C_6D_5CD_3$, 3 M MeI at 38, 30, and 20 °C, 1 M MeI at 20 °C; C_6D_6, 3 M MeI at 38, 30, and 20 °C; $CDCl_3$ 3 M MeI at 20, 10, and 0 °C, 1 M MeI at 20 °C.

The initial product of reductive elimination from **2a** was bis(diphenylmethylphosphine)palladium(0), which can disproportionate to metallic palladium and tetrakis(diphenylmethylphosphine)palladium(0), depending on the reaction solvent.[1]

Mass spectra were obtained on a AEI-MS902 high-resolution mass spectrometer as follows. The palladium complex was dissolved in the appropriate degassed solvent. The solution was then frozen, CD_3I was added, and the reaction vessel was degassed again. The reaction mixture was then allowed to warm to ambient temperature and the reaction was allowed by proceed for 24 h. The evolved gas was then analyzed. The iodomethylpalladium(II) products were isolated by removing the solvent under reduced pressure ($CHCl_3$, C_6H_6) or precipitating the product with pentane, followed by recrystallization. The products were identified by comparison with authentic samples obtained by the oxidative addition reaction of methyl iodide to the corresponding palladium(0) complex.[1]

Because a fragmentation peak at *m/e* 30 in the spectrum of trideuterioethane interferes with the parent peak of ethane, the peak at *m/e* 27 for ethane which appeared in a ratio of 33:26 (*m/e* 27:30) with the parent ion was used to obtain the C_2H_6 ratio. The parent peak at 33 was used for trideuterioethane (Table III).

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Supplementary Material Available: Table IV, ^1H NMR chemical shifts, and coupling constants of dimethylpalladium and iodomethylpalladium complexes **2a**, **10a**, and **10b** in different solvents (1 page). Ordering information is given on any current masthead page.

Regioselective Carbonyl Amination Using Diisobutylaluminum Hydride

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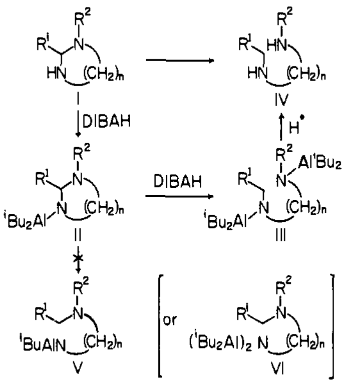
Abstract: A new, selective, and mild approach to N-alkylation of polyamines has been demonstrated, which involves the novel reductive cleavage of the C–N bond in cyclic amidines by diisobutylaluminum hydride. This method provides a new entry to a wide variety of N-alkylated polyamines and many interesting macrocyclic polyamines hitherto accessible only by lengthy or complicated synthesis.

The N-alkylation reaction of amines has long been recognized to be one of the most fundamental reactions for the formation of carbon–nitrogen bonds.[2] However, the alkylation of polyamines is often accompanied by di- or polyalkylations such that the separation of the desired monoalkylated polyamine from the reaction mixture is at best complicated. The hitherto available methodologies for monoalkylation are partially useful only when a large excess of polyamines is used. Therefore, a selective monoalkylation of polyamines has still been awaited with interest.[3]

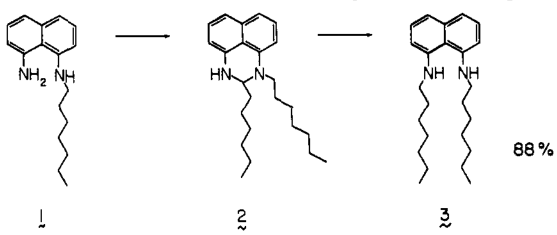
During the course of an investigation into the chemistry of cyclic polyamines and their metal cation inclusion complexes, we devised a new, selective, and mild approach to monoalkylation of polyamines, which involves the novel reductive cleavage of aminals and amidines[4] by diisobutylaluminum hydride (DIBAH).[5]

The general type of transformation which is described herein is summarized in Scheme I. DIBAH is an effective and selective reducing agent which cleanly converts the aluminum amide II[6] to the bis(aluminum amide) III,[7] leading to the monoalkylated 1,(n + 2)-diamine IV after hydrolysis.[8] The reaction should proceed regioselectively, since the formation of the aluminum imide V (or dialuminum amide VI) would be energetically much less favorable.[5,9]

Scheme I



Our process is typified by the conversion of N-heptyl-1,8-diaminonaphthalene (**1**) to N,N'-diheptyl-1,8-diaminonaphthalene (**3**). Treatment of **1** in benzene with heptaldehyde (1 equiv) gave the 1-heptyl-2-hexyl-2,3-dihydroperimidine (**2**) in quantitative yield.[10] Reduction of **2** with DIBAH (6 equiv) in n-hexane afforded the diamine **3** as the major product, which was diluted



1 **2** **3**

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[6] The formation of II was supported by the treatment of the perimidine **2** with 1 equiv of DIBAH at 0 °C to evolve 1 equiv of hydrogen gas.

[7] Aminals are in rapid equilibrium with their imine forms. One may simply be seeing rapid transformation of II to the imine form, followed by the imine reduction here. However, treatment of **6** or **12**, which gives no imine form, with DIBAH under the comparable conditions afforded the corresponding C–N bond cleavage product. Therefore, we support the reducing ability of DIBAH toward the C–N bond.

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[9] In the presence of excess DIBAH, tertiary amine in II (R^2 = alkyl) should coordinate to another DIBAH, while another amide nitrogen would be stabilized by the adjacent aluminum. Therefore, cleavage of the C–N bond between the R^1 and R^2 groups would be favored. Furthermore, formation of an aluminum imide like V generally requires much higher energy compared to that of an aluminum amide (cf. ref 5a, pp 229–232).

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