J. Org. Chem. **1995**, *60*, 1713−1719

Efficient Catalysis of Hydrodediazoniations in Dimethylformamide[1]

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Received August 2, 1994 (Revised Manuscript Received January 9, 1995®)

For hydrodediazoniations (the replacement of a diazo group by hydrogen) in DMF, several substances act as catalysts through their ability to serve as electron donors and initiate free-radical reactions. A general procedure has been developed in which $FeSO_4$ speeds the conversion and leads to higher yields. Trapping experiments demonstrated the presence of free-radical intermediates. *N,N*-Dimethylacetamide was found to rival DMF as a source of hydrogen atoms.

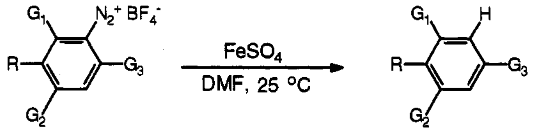
Introduction

Hydrodediazoniation, the replacement of a diazonium group with hydrogen, is an important aromatic substitution reaction that has been a focus of synthetic investigations for over 100 years.[3] It is used chiefly as a method to remove aromatic amino groups after they have been used for positional control in electrophilic aromatic substitution reactions. Numerous organic and inorganic hydrogen donors have been identified for this reaction, but hypophosphorous acid has become the standard.[4] Dimethylformamide[5−7] and a number of structurally related organic compounds including tetramethylurea[8] and formamide[9] have been investigated as hydrogen donor alternatives to hypophosphorous acid.

Herein we report that hydrodediazoniations in DMF are catalyzed by a number of substances which act as electron donors and promote free-radical reactions. These findings are consonant with our earlier observations.[10,11] In addition, we have extended a method used to trap free-radical intermediates and applied the new test to catalyzed and uncatalyzed dediazoniations in DMF.

Results and Discussion

2,4,6-Tribromobenzenediazonium tetrafluoroborate (TFB) (**1a**) and 4-tritylbenzenediazonium TFB (**1b**) were chosen as model reduction substrates. Compound **1a** represents an aromatic diazonium salt possessing electron-withdrawing substituents while **1b** lacks such groups. The reduction products resulting from these diazonium salts (1,3,5-tribromobenzene and tetraphenylmethane) are well characterized solids and are easily isolated. The syntheses of TFBs **1a** and **1b** were straightforward. Bromination of aniline in acetic acid afforded 2,4,6-tribromoaniline which was diazotized cleanly and in high yield using butyl nitrite and $Et_2O{\cdot}BF_3$ in CH_2Cl_2.[12] 4-Aminotetraphenylmethane was dissolved in a solution of acetic acid and H_2SO_4 and diazotized by the addition of aqueous $NaNO_2$ at room temperature. The addition of aqueous $NaBF_4$ precipitated the TFB (**1b**).



1a - m **2a - m**

a : $R = H, G_1 = G_2 = G_3 = Br$
b : $R = H, G_1 = G_3 = H, G_2 = C(Ph)_3$
c : $R = Me, G_1 = G_2 = G_3 = Br$
d : $R = H, G_1 = G_3 = H, G_2 = Br$
e : $R = H, G_1 = G_2 = G_3 = Cl$
f : $R = H, G_1 = G_2 = NO_2, G_3 = H$
g : $R = H, G_1 = G_2 = Me, G_3 = NO_2$
h : $R = H, G_1 = G_3 = H, G_2 = NO_2$
i : $R = H, G_1 = Br, G_2 = G_3 = Cl$
j : $R = H, G_1 = G_3 = H, G_2 = Ph$
k : $R = NO_2, G_1 = G_2 = H, G_3 = Me$
l : $R = H, G_1 = G_3 = H, G_2 = Me$
m : $R = H, G_1 = G_3 = H, G_2 = OMe$

The effect of the mild electron donor, $FeSO_4$ (for Fe^{2+}/Fe^{3+}, $E° = -0.771$ V), upon the reduction of the tribromo compound **1a** was investigated first. If the reaction follows an ionic pathway, then the presence of this material should have no beneficial effect. On the other hand, if the reaction follows a free-radical pathway,[13,14] an electron donor, such as $FeSO_4$, should have a remarkable influence. The diazonium salt was dissolved in dimethylformamide and this solution was added to a

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(1) Presented in part at the 207th National Meeting of the American Chemical Society, San Diego, CA, April 1994, ORGN 281.

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Table 1. $FeSO_4$-Catalyzed Reductions of 2,4,6-Tribromobenzenediazonium TFB (1a) in DMF

mol % $FeSO_4$^{a}	time^b	% yield^c
0	15 min	75^d
5	2 min	77
10	<1 min	90
33	<10 s	96
100	<10 s	96

[a] $FeSO_4$:diazonium TFB. [b] Time required for the complete disappearance of the diazonium salt from the reaction mixture, as indicated by 2-naphthol. [c] Isolated yields after sublimation. [d] Yield by GC analysis.

Table 2. Catalyzed Reductions of 4-Tritylbenzenediazonium TFB (1b) in DMF

catalyst	oxidation potential ($E°$, V)^a	mol % catalyst^b	time^c	% yield^d
none	–	0	>48 h	$<82^e$
$FeSO_4$	−0.77	33	>200 min	87
		100	3 min	90
$FeSO_4 + H_3PO_4$	−0.44	20	<1 min	91
		100	<1 min	91
$K_4Fe(CN)_6$	−0.36	20	>100 min	98
		100	>100 min	92
$FeSO_4 + (CO_2H)_2$	−0.02	20	<1 min	91
		100	<1 min	88
ferrocene	−0.40	100	<1 min	*f*
hydroquinone	−0.70	100	<1 min	*f*

[a] Reference 41. [b] Catalyst:diazonium TFB. [c] Time required for the complete disappearance of the diazonium salt from the reaction mixture, as indicated by 2-naphthol. [d] Yield by isolation. [e] TLC showed two components in the broadly melting solid. [f] Product not isolated.

stirred mixture of $FeSO_4{\cdot}7H_2O$ and DMF. Table 1 summarizes the results of the reductions when varied amounts of catalyst were used. In the absence of catalyst, the reaction was complete within 15 min and produced a broadly melting mixture of two products. The addition of as little as 5 mol % of $FeSO_4$ reduced the reaction time to 2 min and gave 77% of pure 1,3,5-tribromobenzene. Further increases in catalyst amounts increased yields to 96% and shortened reaction times to the point that they were no longer easily measured. Clearly, the fact that the addition of $FeSO_4$ enhanced the rate of the reaction and increased the yield of 1,3,5-tribromobenzene is strong evidence for a free-radical pathway.

The reduction of the trityl compound **1b** turned out to be more difficult (Table 2). In the absence of catalyst, the reaction required over 48 h and produced an impure solid. An important comparison was that the reaction time of the uncatalyzed reduction of **1b** was over 150 times that of **1a**. The addition of 100 mol % $FeSO_4$ was required to diminish the reaction time to 3 min and increased the yield of tetraphenylmethane to 90%. Previous work in our laboratory demonstrated that compounds that are better reductants (*i.e.*, compounds that have lower potentials) more effectively initiate the radical reaction.[10] The oxidation potential of iron(II) can be modified by carefully varying its ligands (Table 2). A combination of $FeSO_4$ with additives such as H_3PO_4 or oxalic acid decreases the potential of the ferrous ion from −0.77 V to −0.44 and −0.02 V, respectively. As little as 20 mol % of these new catalysts markedly enhanced the rate of the reaction and improved the yield. Despite a lower potential for $K_4Fe(CN)_6$ (for $[Fe(CN)_6]^{4-}/[Fe(CN)_6]^{3-}$, $E° = -0.36$ V), it was not sufficiently soluble in the reaction medium for a meaningful comparison to be made. Ferrocene and hydroquinone, because they are both good electron donors, also enhanced the rate of the reaction; however, separation of the product from the catalyst proved to be troublesome. Even though we identified a number of more effective catalysts for the reduction of **1b**, 100 mol % $FeSO_4$ was chosen as the standard because of its simplicity and low cost.

Varieties of substituted aromatic diazonium TFBs were reduced in DMF with 100 mol % $FeSO_4$ (Table 3). Dilution of the reaction mixture caused the product to separate. For many solids, the product was of such quality that only filtration and washing with water were necessary to afford pure material. Yields of isolated reduction products were moderate to excellent.

The diazonium salts fell into two classifications. Rings bearing nitro groups or several halogen atoms were more reactive and underwent spontaneous decomposition when dissolved in DMF. Rings bearing electron-donating groups were less reactive and required more catalyst to shorten the reaction time. A similar distinction in reactivity was earlier observed by Marx,[6] and we note that the results of Lahoti and co-workers[7] can be interpreted in the same way. In the catalyzed reactions, increasing the catalyst amounts improves the yields, shortens the reaction times, and serves to blur this distinction in reactivity.

Up to this point the reductions were conducted in the absence of appreciable amounts of water, the only water present coming from the hydrated form of the catalyst being used. We decided to examine the behavior of the

Table 3. $FeSO_4$-Catalyzed Reductions of Aryldiazonium Tetrafluoroborates in DMF

benzenediazonium TFB	compd no.	mol % catalyst^a	product	% yield^b
2,4,6-tribromo	**1a**	100	1,3,5-tribromobenzene	96
4-trityl	**1b**	100	tetraphenylmethane	90
3-methyl-2,4,6-tribromo	**1c**	100	2,4,6-tribromotoluene	95
2,4,6-trichloro	**1e**	100	1,3,5-trichlorobenzene	66
2,4-dinitro	**1f**	100	1,3-dinitrobenzene	73
2,4-dimethyl-6-nitro	**1g**	100	1,3-dimethyl-5-nitrobenzene	72
		33		17
		10		<10
4-nitro	**1h**	100	nitrobenzene	65^c
2-bromo-4,6-dichloro	**1i**	100	1-bromo-3,5-dichlorobenzene	82
4-biphenyl	**1j**	100	biphenyl	84
		20		34
2-methyl-5-nitro	**1k**	100	4-nitrotoluene	56
4-methyl	**1l**	100	toluene	72
4-methoxy	**1m**	100	anisole	68
		33		61

[a] $FeSO_4$:TFB. [b] Isolated yields. [c] Yield by GC analysis.

Table 4. Effect of Water on the $FeSO_4$-Catalyzed Reduction of 3-Methyl-2,4,6-tribromobenzenediazonium TFB (1c)

mol % DMF	% by volume DMF	time[a]	% yield[b]
100	100	<1 min	95
19	50	<1 min	96
3	10	1 min	77
0.2	1	>100 min	81[c]

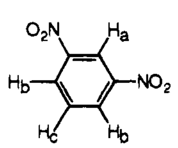
[a] Time required for the complete disappearance of the diazonium salt from the reaction mixture, as indicated by 2-naphthol. [b] Isolated yields. [c] Broadly melting product.

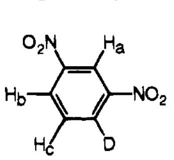
reductions in mixtures of DMF and water. 3-Methyl-2,4,6-tribromobenzenediazonium TFB **1c** served as the test compound for this investigation. The results are displayed in Table 4. There was little change in the reaction time or yield for wide changes in DMF concentration, but the yield of product dropped significantly and the reaction time increased over 100-fold on high dilution of the DMF.

The fact that moderate dilution did not effect the reaction led us to run some reductions with solutions of diazotized amines. 2,4,6-Tribromoaniline and 4-aminobiphenyl were each diazotized in an acetic acid$-H_2SO_4$ solution by the addition of a concentrated aqueous solution of $NaNO_2$, and the diazonium solution was added to the reductant mixture. The yields of the products, pure after sublimation, were 90% for 1,3,5-tribromobenzene and 70% for biphenyl. In another illustration of the method, 1,3-dimethyl-5-nitrobenzene was produced in 74% overall yield, after diazotization of the 2,4-dimethyl-6-nitroaniline in an aqueous solution of HCl. This technique reduces diazonium salts in a matter of minutes compared to the hours or days required for the related reductions using H_3PO_2. Furthermore, the omission of the isolation of the diazonium salt does not have a significant effect upon the yield of the reduction product.

Hydrogen Atom Source. In the neat solvent, DMF must be the sole hydrogen atom source; where the DMF is diluted with water, the situation is not so clear. To clarify the situation, a replacement was conducted in aqueous DMF-d_7. Incorporation of hydrogen into the product would indicate that DMF-d_7 is not the sole atom donor and the water played a role in the reaction. When 2,4-dinitrobenzenediazonium TFB was subjected to catalyzed dediazoniation in aqueous DMF-d_7, only deuterium appeared in the position vacated by the diazonium unit. The result proved that the sole source of hydrogen is the DMF and that none came from the water diluent.

The ^1H NMR spectrum of the product had interesting characteristics. In contrast to ordinary 1,3-dinitrobenzene where the magnitude of the H_a, H_b, and H_c absorptions occur in the order 1:2:1, in the deuterium product, the order is 1:1:1. Likewise, the splitting for the three





positions changes from singlet, doublet, triplet for the ordinary material to singlet, doublet, doublet for the product which had incorporated deuterium. In combination with the chemical shifts, the spectral properties can be accounted for only by complete deuterium incorporation in the position vacated by the diazonium unit. In addition, mass spectral analysis of the product independently showed that deuterium incorporation was at least 99.5%. The utility of our method for the monodeuteration of aromatic rings is described elsewhere.[15]

Table 5. Catalyzed Hydrodediazoniations of 2,4,6-Tribromobenzenediazonium TFB (1a) in Solvents Structurally Related to DMF

solvent	time[a]	% yield[b]
tetramethylurea	<1 min	96
N,N-dimethylacetamide	<1 min	97
N,N-dimethylformamide	<1 min	96
formic acid	>180 min	40
methyl formate	>180 min	61

[a] Time required for the complete disappearance of the diazonium salt from the reaction mixture, as indicated by 2-naphthol. [b] Yields of isolated product after sublimation.

Within DMF the hydrogen atom source can be either the formyl hydrogen or any one of the six *N*-methyl hydrogens. To investigate the hydrogen source we studied the $FeSO_4$-catalyzed reaction of **1a** in two sets of solvents structurally related to DMF (Table 5). The first set, composed of tetramethylurea and *N,N*-dimethylacetamide, contained compounds with *N*-methyl hydrogens and no formyl hydrogen. Reactions in both substances were fast and resulted in high yields of product. Certainly the *N*-methyl groups can serve as the source of the hydrogen atoms. The second set, composed of methyl formate and formic acid, contained compounds with formyl hydrogens but no *N*-methyl hydrogens. This set of reductants proved to be less reactive. Clearly both sites can furnish hydrogen. Our results concur with those of Doyle *et al.* in their study of the hydrogen atom abstraction site in DMF in a related reaction.[16] Furthermore, Minisci *et al.*[17] also showed the proportion of *N*-methyl to formyl hydrogen atom abstraction to be 60:40. All of these results, taken together, suggest that the major site of hydrogen atom abstraction is principally the *N*-methyl group.

Mechanism. Our catalyst studies strongly implicate the following free-radical chain mechanism:

$$Fe^{2+} + ArN_2^{+} \rightarrow Fe^{3+} + ArN_2^{\bullet} \qquad (1)$$

$$ArN_2^{\bullet} \rightarrow Ar^{\bullet} + N_2 \qquad (2)$$

$$Ar^{\bullet} + HCON(CH_3)_2 \rightarrow ArH + HCON(CH_3)CH_2^{\bullet} \text{ and } \dot{C}ON(CH_3)_2 \qquad (3)$$

$$ArN_2^{+} + HCON(CH_3)CH_2^{\bullet} \text{ (or } \dot{C}ON(CH_3)_2) \rightarrow ArN_2^{\bullet} + HCON(CH_3)CH_2^{+} \text{ (or } {}^{+}CON(CH_3)_2) \qquad (4a)$$

$$Fe^{3+} + HCON(CH_3)CH_2^{\bullet} \text{ (or } \dot{C}ON(CH_3)_2) \rightarrow Fe^{2+} + HCON(CH_3)CH_2^{+} \text{ (or } {}^{+}CON(CH_3)_2) \qquad (4b)$$

The ferrous ion reduces the diazonium cation to the diazenyl radical (eq 1), which undergoes cleavage to form molecular nitrogen and the aryl radical (eq 2). The aryl radical abstracts hydrogen from DMF (eq 3) producing

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[15] Wassmundt, F. W.; Kiesman, W. F. *J. Labelled Compd. Radiopharm*, in press.

[16] Doyle, M. P.; Dellaria, J. F.; Siegfried, B.; Bishop, S. W. *J. Org. Chem.* **1977**, *42*, 3494. In an approach using alkyl nitrites to deaminate aromatic amines in DMF, these authors postulate a free-radical pathway without the intermediacy of a diazonium cation.

[17] Gardini, G. P.; Minisci, F.; Palla, G.; Arnone, A.; Galli, R. *Tetrahedron Lett.* **1971**, 59.

ArH and one of the isomeric radicals derived from the solvent. The radical chain reaction is propagated when more diazonium salt oxidizes one of the solvent derived radicals (eq 4a) and forms the diazenyl radical. Alternatively, the ferric ion formed in the initiation reaction can act as an oxidant to the solvent derived radicals and regenerate the ferrous ion (eq 4b).

All of the evidence gathered during our study of the catalyzed hydrodediazoniation is consistent with the free radical chain mechanism. The ferrous ion acts as an electron donor for diazonium ions (eq 1). This point was well established not only by our observation of the dramatic accelerating effect that catalysts had upon the hydrodediazoniations of the model compounds (Tables 1 and 2) but also by the fact that as the catalyst became a better electron donor (*i.e.*, its potential was lowered) smaller amounts of it could be used to initiate the reaction. The activity of ferrous ion as catalyst for free-radical diazonium salt reactions has also been noted by others.[13,14]

For the presence of the aryl radical (eq 2), we sought a confirmatory test. Bunnett and Wamser[18] as well as Brydon and Cadogen[19] have demonstrated that aryl radicals readily abstract iodine from iodobenzene. In effect, the iodobenzene acts as an iodine atom donor and serves as a trap for the aryl radical.[20] Therefore, the replacement of the diazonium group by iodine would demonstrate the presence of an aryl radical. For our purposes, we chose 4 iodobenzoic acid as the iodine atom donor. This choice of trapping agent simplified the analysis of the product, because any surplus could easily be removed by washing with base. 4-Bromobenzenediazonium TFB (**1d**) was subjected to the catalyzed hydrodediazoniation conditions in the presence of 2 equiv of the 4-iodobenzoic acid. The only neutral solid product that resulted was 4-bromoiodobenzene. Isolation of this product conclusively demonstrated the presence of the 4-bromophenyl radical (eq 2).

We showed previously that DMF was the sole hydrogen atom source and that both the formyl and *N*-methyl hydrogen atoms were susceptible to radical abstraction; these observations can be expained by eq 3.

The results in Tables 1 and 2 show that less than molar amounts of the catalyst can be used to speed the reaction and increase the yields; the results are consistent with the chain propagating steps (eqs 4a and 4b). Each step in our proposed mechanism is directly supported by experimental observations.

Diazonium salts bearing strong electron-withdrawing groups, we noted earlier, underwent spontaneous reactions when dissolved in DMF. Earlier workers regarded the hydrodediazoniation in DMF as an ionic process.[6,7] Because of the lack of direct evidence to support this assertion, it seemed worthwhile for us to apply the new radical trapping procedure to the uncatalyzed reaction. 4-Bromobenzenediazonium TFB (**1d**) and 2 equiv of 4-iodobenzoic acid were dissolved in DMF. The sole neutral solid product of the reaction was 4-bromoiodobenzene. The trapping agent had here again intercepted the 4-bromophenyl radical. In another example, the uncatalyzed reduction of 2,4,6-trichlorobenzenediazonium TFB (**1e**) was examined. GC/MS analysis of the resulting solid material showed it to be a mixture of 1,3,5-trichlorobenzene and 2-iodo-1,3,5-trichlorobenzene. Again the trap had intercepted an aryl radical intermediate. These results clearly demonstrated that the uncatalyzed hydrodediazoniations in DMF, like their catalyzed counterparts, proceed through the common aryl radical intermediate (eqs 2 and 3).

Table 6. $FeSO_4$-Catalyzed Reductions of Aryldiazonium Tetrafluoroborates in *N,N*-Dimethylacetamide

benzenediazonium TFB	product	% yield[a]
2,4-dinitro	1,3-dinitrobenzene	60
2,4,6-tribromo	1,3,5-tribromobenzene	97
4-trityl	tetraphenylmethane	94
4-methoxy	anisole	64[b]

[a] Isolated yields. [b] Yield by GC analysis.

With the evidence for the intermediacy of free radicals in hand, we envision two possible modes of initiation. One involves an electron transfer from the DMF to the

$$\mathrm{ArN_2}^+ + \mathrm{HCON(CH_3)_2} \rightarrow \mathrm{ArN_2}^{\bullet} + \mathrm{HCON}^{\bullet+}\mathrm{(CH_3)_2} \qquad (5)$$

diazonium ion (eq 5). The second mode of initiation involves an ionic coupling at either the nitrogen atom or the oxygen atom of DMF followed by a homolytic bond cleavage (eq 6).

$$\begin{gathered}\mathrm{ArN_2}^+ + \mathrm{HCON(CH_3)_2} \rightarrow \mathrm{ArN{=}N{-}N(HCO)(CH_3)_2}^+ \\ \text{or} \qquad (6) \\ \mathrm{ArN{=}N{-}OCHN(CH_3)_2}^+ \rightarrow \mathrm{ArN_2}^{\bullet} + \mathrm{HCON}^{\bullet+}\mathrm{(CH_3)_2}\end{gathered}$$

Diazonium ions with electron-withdrawing groups are powerful oxidizing agents and have been observed to capture electrons from polycyclic arenes[21] or from tertiary amines.[13] The oxidation potential of DMF (> 1.0 V) would undoubtedly make it less effective electron donor when compared to polycyclic arenes or tertiary amines; however, in a free radical chain mechanism only a very small number of initiations would allow the reaction to run to completion. In the alternative (eq 6), the pathway is similar to that proposed by Tröndlin and Rüchardt[22] for the initiation of uncatalyzed hydrodediazoniations in HMPA. From the high oxidation potential of DMF, the more likely pathway for initiation would be the coupling pathway (eq 6).

The chain propagating step (eq 4a) for the uncatalyzed reaction is likely the same as for the catalyzed reaction.

N,N-Dimethylacetamide was an effective hydrogen donor in the reduction of **1a** (Table 5) and was therefore an attractive target for further study. Representative diazonium salt examples were reduced in dimethylacetamide with 100 mol % $FeSO_4$ as a catalyst (Table 6). The yields of products are comparable with those obtained using DMF. Trapping experiments with 4-iodobenzoic acid were performed on both the uncatalyzed and catalyzed reductions of 4-bromobenzenediazonium TFB (**1d**) in dimethylacetamide. The results showed that the radical pathway was followed in both situations. In contrast, the spontaneous decomposition of diazonium salts with multiple electron-withdrawing groups that was found to occur in DMF did not take place when dimethyl-

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acetamide was employed as the reaction solvent. Dimethylacetamide, although it appears to be slightly less reactive, is nevertheless an excellent reactant, and yields of products achieved with it rival those with DMF.

Conclusions

Several catalysts have been discovered for hydrodediazoniations conducted in DMF. The discovery permitted the development of a general technique with $FeSO_4$ which, under mild conditions, quickly and efficiently replaces the diazonium group with hydrogen regardless of the electronic character of the groups on the aromatic ring. The catalysts serve as electron donors to initiate a free-radical reaction; the free-radical nature of the reaction was confirmed by trapping studies.

N,N-Dimethylacetamide can replace DMF and also provides good results.

To the extent that the reaction with DMF can serve as a prototype for uncatalyzed hydrodediazoniations in general, our studies show that the reactions are autocatalytic free-radical reactions, provided the groups on the aromatic ring of the diazonium salt are sufficiently electron withdrawing to capture an electron from the coreactant, often the solvent. Where such groups are lacking, the reduction is extremely slow and the diazonium salt is diverted by competing reactions. The catalysts are electron-donors which initiate fast free-radical reactions and provide high yields. Catalysts benefit the reduction, regardless of the electronic characteristics of the groups attached to the aromatic ring, although diazonium salts with electron-donating groups may require more catalyst.

Experimental Section

General. Melting points are uncorrected.

2,4,6-Tribromobenzenamine. This amine was prepared by the method described by Pedemonte.[10] Bromine (16.5 mL, 0.33 mol) was added dropwise with stirring to a solution of 10.0 g (0.11 mol) of aniline in 50 mL of glacial acetic acid. The solution was stirred for an additional 5 min and then poured into 200 mL of ice−water. The off-white product was collected by suction filtration and recrystallized from 95% ethanol to afford 31.4 g (87%) of white needles melting at 119−120 °C (lit.[23] mp 119−120 °C).

2-Bromo-4,6-dichlorobenzenamine was prepared from 2,4-dichlorobenzenamine in a manner similar to that for 2,4,6-tribromobenzenamine, 6.15 g (82%) of 2-bromo-4,6-dichlorobenzenamine as white needles, mp 80−81 °C (lit.[24] mp 81.5 °C).

3-Methyl-2,4,6-tribromobenzenamine was prepared from 3-toluidine in a manner similar to that for 2-bromo-4,6-dichlorobenzenamine, quantitative yield of the crude product, mp 100−101 °C (lit.[25] mp 100−101 °C).

4-Aminotetraphenylmethane. This compound was prepared by the procedure described by Reid and Witten[26] from triphenylmethanol, aniline hydrochloride, acetic acid, and sulfuric acid. The pure amine (25.3 g, 65%) melted at 253−254 °C (lit.[26] mp 249−250 °C).

4-Tritylbenzenediazonium Tetrafluoroborate (1b). This compound was prepared by the method described by Pedemonte.[10] 4-Aminotetraphenylmethane (5.00 g, 14.9 mmol) was dissolved by heating in 30 mL of acetic acid and 2.1 mL (37.0 mmol) of concd H_2SO_4. The solution was then cooled to 10 °C in an ice-bath with vigorous stirring to precipitate a finely divided solid which was diazotized by the slow addition of 1.05 g (15.0 mmol) of $NaNO_2$ in 5 mL of water. After an additional 15 min of stirring, the surplus nitrous acid was destroyed by the addition of sulfamic acid, and the solution was filtered to remove a trace amount of solid. The filtrate was recooled and the diazonium tetrafluoroborate precipitated by the addition of 2.87 g (26.0 mmol) of $NaBF_4$ in 15 mL of water. The diazonium salt was collected by suction filtration, washed with ether, and dried in a vacuum desiccator overnight to afford 6.02 g. The crude salt was purified by precipitation from its solution in reagent-grade acetone by the addition of ether. Repetition of the purification process afforded 5.70 g (88%) of pure diazonium TFB, mp 237−238 °C (lit.[10] mp 237−238 °C).

4-Biphenyldiazonium tetrafluoroborate (1j) was prepared in a similar manner to **1b**, from 4-biphenylamine in 65% yield; mp 116−117 °C dec (lit.[4a] mp 116 °C dec).

2,4,6-Tribromobenzenediazonium Tetrafluoroborate (1a). This compound was prepared by the method described by Doyle and Bryker[12] with minor modifications. To a 100-mL three-neck flask equipped with a magnetic stirrer, condenser, and two addition funnels was added 2.4 mL (9.10 mmol) of $BF_3{\cdot}Et_2O$. The $BF_3{\cdot}Et_2O$ was chilled to −10 to −15 °C in an ice−acetone bath, and to it was added a solution of 2.00 g (6.06 mmol) of tribromobenzenamine in 20 mL of CH_2Cl_2. A precipitate formed; to facilitate mixing an additional 30 mL of CH_2Cl_2 was added to the reaction mixture. A solution of 0.751 g (7.28 mmol) of butyl nitrite in 10 mL of CH_2Cl_2 was added dropwise with stirring over a 10 min period. The reaction mixture was stirred for an additional 30 min at −15 °C and then allowed to warm, over a 20 min period, to 5 °C in an ice−water bath. The reaction mixture was poured into 100 mL of pentane to fully precipitate the product. The white solid was collected, washed with ether, and dried to give 2.525 g (97%) of crude product. TLC of the product (silica, CH_2Cl_2) indicated the presence of amine. The product was purified by the acetone−ether method to yield 2.417 g (93%) of the white diazonium salt; mp 248−249 °C (lit.[10] mp 245 °C dec).

The following diazonium salts were prepared in an analogous manner.

3-Methyl-2,4,6-tribromobenzenediazonium tetrafluoroborate (1c): from 3-methyl-2,4,6-tribromoaniline, 36% yield, mp 230.5−231.5 °C dec. Anal. Calcd for $C_7H_4BBr_3F_4N_2$: C, 18.99; H, 0.91; N, 6.33. Found: C, 19.43; H, 0.50: N, 6.35.

4-Bromobenzenediazonium tetrafluoroborate (1d): from 4-bromoaniline, 61% yield, mp 134.5 °C dec (lit.[10] mp 133 °C dec).

2,4,6-Trichlorobenzenediazonium tetrafluoroborate (1e): from 2,4,6-trichloroaniline, 83% yield, mp 188−189 °C dec (lit.[4a] mp 187 °C dec).

2,4-Dinitrobenzenediazonium tetrafluoroborate (1f): from 2,4-dinitroaniline; 1,2-dimethoxyethane was the solvent of choice for this diazotization; 56% yield, mp 165−167 °C dec (lit.[27] mp 156 °C dec).

2,4-Dimethyl-6-nitrobenzenediazonium Tetrafluoroborate (1g): from 2,4-dimethyl-6-nitroaniline, 63% yield, mp 161−162 °C dec (lit.[10] mp 161−162 °C dec).

4-Nitrobenzenediazonium Tetrafluoroborate (1h): from 4-nitroaniline; 1,2-dimethoxyethane was the solvent of choice for this diazotization; 85% yield, mp 156.5−157.5 °C dec (lit.[28] mp 156 °C dec).

2-Bromo-4,6-dichlorobenzenediazonium tetrafluoroborate (1i): from 2-bromo-4,6-dichloroaniline, 64% yield, mp 225−225.8 °C dec (lit.[10] mp 196−197 °C dec).

4-Methylbenzenediazonium tetrafluoroborate (1l) was prepared by the method described by Roe[29] from 4-toluidine (10.00 g, 0.093 mol), 80% yield, mp 108−108.5 °C dec (lit.[30] mp 110 °C).

4-Methoxybenzenediazonium tetrafluoroborate (1m) was prepared similar to **1l**. The crude diazonium salt was

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purified by the acetone–ether method to yield 48.74 g (90%) of white product, mp 139–140 °C dec (lit.[31] mp 139 °C).

General Procedure for Reductions in *N,N*-Dimethylformamide: 1,3,5-Tribromobenzene (2a). **1a** (0.500 g, 1.17 mmol) was dissolved in 2 mL of DMF and added dropwise with stirring to 0.324 g (1.17 mmol) $FeSO_4\cdot 7H_2O$ in 10 mL of DMF at rt. Immediately after the final addition, the reaction mixture tested negative to 2-naphthol for the presence of diazonium salt, and the light yellow solution was poured into 70 mL of water. The resulting white precipitate was collected by suction filtration, washed with water, and dried in a vacuum desiccator; 0.354 g (96%) of 1,3,5-tribromoenzene as a white solid was recovered, mp 120–120.5 °C (lit.[32] mp 120–121 °C).

In modifications of the above procedure, the reduction was repeated with 0.033 g (0.12 mmol), and 0.016 g (0.06 mmol) of $FeSO_4\cdot 7H_2O$. Reaction times were 10 sec and 2 min and yields of pure sublimed products were 0.320 g (90%) and 0.284 g (77%), respectively. Omission of catalyst increased the reaction time to 15 min; sublimation yielded 0.257 g (82%) of a solid, mp 113–118 °C (lit.[32] mp 120–121 °C).

The following substances were formed in reductions by the general procedure.

Tetraphenylmethane (2b): from **1b** (0.500 g, 1.15 mmol), $FeSO_4\cdot 7H_2O$ (0.321 g, 1.15 mmol), and 10 mL of DMF; 0.333 g (90%) after sublimation, mp 281–281.5 °C (lit.[33] mp 285 °C).

When the above reduction was repeated with 0.107 g (0.38 mmol) of $FeSO_4\cdot 7H_2O$, the reaction time increased to more than 180 min and the yield of sublimed product was 0.322 g (87%). Omission of catalyst increased the reaction time to more than 24 h and after sublimation yielded 0.304 g (82%) of product, mp 279–280 °C.

1-Methyl-2,4,6-tribromobenzene (2c): from **1c** (0.450 g, 1.02 mmol), $FeSO_4\cdot 7H_2O$ (0.284 g, 1.02 mmol), and 10 mL DMF; 96% yield, mp 66.5–68 °C (lit.[25] mp 68.5 °C); ^1H NMR (270 MHz, $CDCl_3$) δ 7.65 (s, 2H), 2.5 (s, 3H).

1,3,5-Trichlorobenzene (2e): from **1e** (0.600 g, 2.03 mmol), $FeSO_4\cdot 7H_2O$ (0.565 g, 2.03 mmol), and 10 mL of DMF; 73% yield, mp 61–62 °C (lit.[34] mp 63.4 °C).

1,3-Dinitrobenzene (2f): from **1f** (0.500 g, 1.77 mmol) dissolved in acetone, $FeSO_4\cdot 7H_2O$ (0.493 g, 1.77 mmol), and 10 mL of DMF; 0.240g (81%) crude yield, mp 87–88 °C; 0.216 g (73%) yield after sublimation, mp 89–89.5 °C (lit.[35] mp 88 °C); ^1H NMR (270 MHz, $CDCl_3$) δ 9.08 (s, 1H), 8.63 (d, 2H), 7.86 (t, 1H).

1,3-Dinitro[4-D]benzene: from **1f** (0.100 g, 0.35 mmol), $FeSO_4\cdot 7H_2O$ (0.99 g, 0.35 mmol), 4 mL of water, and 1 mL of DMF-d_7. The reaction mixture was poured into 4 mL of water, and the product was collected by suction filtration; 0.030 g (51%) after sublimation, mp 89–89.5 °C (lit.[35] mp 88 °C); ^1H NMR (270 MHz, $CDCl_3$) δ 9.08 (s, 1H), 8.62 (d, 1H), 7.86 (d, 1H).

1,3-Dimethyl-5-nitrobenzene (2g): from **1g** (0.550 g, 2.08 mmol) dissolved in acetone, $FeSO_4\cdot 7H_2O$ (0.577 g, 2.08 mmol), and 10 mL of DMF; 0.242 g, 77% crude yield, mp 68–70 °C, 0.226 g, 72% yield after sublimation, mp 70.5–71 °C (lit.[36] mp 72 °C).

Nitrobenzene (2h); from **1h** (1.00 g, 4.22 mmol), $FeSO_4\cdot 7H_2O$ (1.173 g, 4.22 mmol), and 10 mL of DMF, (65%) (calcd from GC analysis) after extraction with CH_2Cl_2, and drying.

1-Bromo-3,5-dichlorobenzene (2i): from **1i** (0.500 g, 1.47 mmol), $FeSO_4\cdot 7H_2O$ (0.409 g, 1.47 mmol), and 10 mL of DMF; 0.288 g (87%), mp 74–75 °C (lit.[37] mp 74 °C).

4-Biphenyl (2j): from **1j** (0.500 g, 1.87 mmol), $FeSO_4\cdot 7H_2O$ (0.519 g, 1.87 mmol), and 10 mL of DMF; 0.241 g (84%) after sublimation, mp 68.5–69 °C (lit.[38] mp 69 °C).

4-Nitrotoluene (2k): from **1k** (0.500 g, 1.99 mmol), $FeSO_4\cdot 7H_2O$ (0.554 g, 1.99 mmol), and 10 mL of DMF; 0.171 g (56%) after sublimation, mp 53–54 °C (lit.[35] mp 54 °C).

Methylbenzene (2l): from **1l** (13.65 g, 0.066 mol), $FeSO_4\cdot 7H_2O$ (18.44 g, 0.066 mol), and 110 mL of DMF; 4.387 g (72%) after steam distillation, extraction with CH_2Cl_2, decolorization with charcoal, and drying, bp 109–111 °C (lit.[39] bp 110.8 °C).

Methoxybenzene (2m): from **1m** (16.00 g, 0.072 mol), $FeSO_4\cdot 7H_2O$ (20.04 g, 0.072 mol), and 110 mL of DMF; 5.279g (68%) after steam distillation, extraction with CH_2Cl_2, decolorization with charcoal, and drying, bp 153–155 °C (lit.[40] bp 153.9 °C).

Reduction in *N,N*-Dimethylformamide without Isolation of the Diazonium Salt Intermediate: 1,3,5-Tribromobenzene (2a). 2,4,6-Tribromoaniline (0.500 g, 1.52 mmol) was dissolved in a warm solution of concd H_2SO_4 (0.224 g, 2.28 mmol) and 2 mL of glacial acetic acid. The solution was allowed to cool to rt, and a solution of 0.117 g (1.67 mmol) of $NaNO_2$ in 1 mL of water was added dropwise over a 20 min period. The reaction mixture was stirred for an additional 15 min and was then added with stirring to a mixture of 0.432 g (1.52 mmol) of $FeSO_4\cdot 7H_2O$ in 20 mL of DMF. The reaction solution was negative to 2-naphthol immediately after the last addition. Pouring into 75 mL of water precipitated a light tan product which was collected by suction filtration, washed with water, and dried; it gave 0.430 g (90%) of 1,3,5-tribromobenzene melting at 119.6–121 °C (lit.[32] mp 120–121 °C).

4-Biphenyl (2j): from 4-aminobiphenyl (0.500 g, 3.00 mmol), $FeSO_4\cdot 7H_2O$ (0.835 g, 3.00 mmol), and 10 mL of DMF; 0.325 g (70%) after sublimation, mp 68.5–69 °C (lit.[38] mp 69 °C).

1,3-Dimethyl-5-nitrobenzene (1g). A solution of 2,4-dimethyl-6-nitroaniline (0.250 g, 1.50 mmol) in 1 mL of acetic acid was added to a mixture of 0.54 mL of concd HCl and 3.0 g of ice. A concentrated solution of $NaNO_2$ (0.114 g, 1.62 mmol) was added dropwise with stirring. The reaction mixture was stirred for an additional 15 min, and then sulfamic acid was added to the diazonium solution to destroy any remaining nitrous acid. The solution of the diazotized amine was added dropwise with stirring to a mixture of $FeSO_4\cdot 7H_2O$ (0.417 g, 1.50 mmol) and 5 mL of DMF. The reaction solution was negative to 2-naphthol immediately after the last addition. Pouring into 75 mL of water precipitated a light yellow product which was collected by suction filtration, washed with water, and dried. There resulted 0.173 g (76%) of 1,3-dimethyl-5-nitrobenzene, mp 68–69 °C. After sublimation 0.169 g (74%), mp 70–70.5 °C (lit.[25] mp 72 °C).

Trapping Experiments: Catalyzed Reductions in Various Solvents. 4-Iodobenzoic acid (0.183 g, 0.74 mmol) and $FeSO_4\cdot 7H_2O$ (0.103 g, 0.37 mmol) were added to 2 mL of DMF. Solid **1d** (0.100 g, 0.37 mmol) was added gradually with stirring to the DMF solution. The reaction was over immediately, and the solution was poured into 10 mL of 5% KOH. This mixture was stirred for 10 min, and the solid products were collected by suction filtration, washed with water, and dried. At least 97% of the 35 mg of neutral solid was 4-bromoiodobenzene; MS m/z (M^+) calcd 281.85, obsd 281.90.

In *N,N*-dimethylacetamide, under identical conditions, 4-bromoiodobenzene was the major product; MS m/z (M^+) calcd 281.85, obsd 281.85.

Trapping Experiments: Uncatalyzed Reductions in Various Solvents. Solid **1e** (0.500 g, 1.69 mmol) was added gradually with stirring to 4-iodobenzoic acid (0.838 g, 3.38 mmol) in 10 mL of DMF. The reaction was complete in 45 min, and the solution was poured into 80 mL of 5% KOH. This mixture was stirred for 10 min, and the solid products were collected by suction filtration, washed with water, and dried. GC/MS analysis of the solid indicated a 97:3 mixture of 1,3,5-trichlorobenzene: 2-iodo-1,3,5-trichlorobenzene; MS m/z (M^+) calcd 179.93, obsd 179.90: calcd 305.82, obsd 305.79.

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Solid **1d** (0.100 g, 0.37 mmol) was added gradually with stirring to 4-iodobenzoic acid (0.183 g, 0.74 mmol) in mL of DMF. The reaction was stirred overnight, and the solution was poured into 10 mL of 5% KOH. This mixture was stirred for 10 min, and the solid products were collected by suction filtration, washed with water, and dried. The main product of the reaction, constituting 97% of the recovered solid, was 4-bromoiodobenzene; MS *m/z* (M^+) calcd 281.85, obsd 281.90.

In *N,N*-dimethylacetamide, under identical conditions, 4-bromoiodobenzene was the major product; MS *m/z* (M^+) calcd 281.85, obsd 281.85.

Acknowledgment. This material is based upon work supported under a National Science Foundation Graduate Research Fellowship.

JO9413303