bis(methylthio) alcohols in extremely high yield. Reduction of systems bearing a C-2 substituent other than methyl, i.e., **22**, are also reduced stereospecifically; however, the yield is somewhat lower. This study clearly demonstrates that α-oxo ketene dithioacetals, which are readily available from ketones, carbon disulfide, and an alkylating agent, provide a new and interesting entry to acyclic stereocontrol.

Further studies exploiting the synthetic potential of α-oxo ketene dithioacetals and in particular taking advantage of the stereochemically defined nature of the organometallic intermediate B will be reported in due course.

Registry No. 1, 32268-43-2; **2**, 74291-93-3; **3**, 61541-58-0; **4**, 91002-91-4; **5**, 17649-86-4; **6**, 91002-92-5; **7**, 51507-09-6; **8**, 91002-93-6; **9**, 17649-89-7; **10**, 91002-94-7; **11**, 17649-90-0; **12**, 91002-95-8; **13**, 78078-05-4; **14**, 91002-96-9; **15**, 91002-97-0; **16**, 91002-98-1; **17**, 51507-08-5; **18**, 84307-86-8; **19**, 91002-99-2; **20**, 91003-00-8; **21**, 91003-01-9; **22**, 91003-02-0; **23**, 91003-03-1; **24**, 91032-20-1; $LiAlH_4$, 16853-85-3.

Ronald B. Gammill,* Larry T. Bell, Sharon A. Nash

Atherosclerosis and Thrombosis Research
The Upjohn Company, Kalamazoo, Michigan 49001

Received March 28, 1984

Ferrous Ion Catalysis of Reactions of Nucleophiles with Aryl Halides[1]

Summary: Reactions of ketone enolate ions and of diethyl phosphite ion with bromo- and iodobenzene in ammonia or dimethyl sulfoxide solution occur in preparatively useful amounts under catalysis by iron(II) salts, apparently via the $S_{RN}1$ mechanism.

Sir: In the recent decade it has been demonstrated in several instances that plain aryl halides, without electron-attracting activating substituents, often react very satisfactorily with nucleophiles providing that reaction is appropriately provoked. Of major interest among such processes are reactions that occur by the radical chain $S_{RN}1$ mechanism.[2] The propagation cycle for this mechanism is shown in Scheme I.

Scheme I

$$ArX\cdot^- \rightarrow Ar\cdot + X^- \qquad (M1)$$

$$Ar\cdot + Y^- \rightarrow ArY^-\cdot \qquad (M2)$$

$$ArY^-\cdot + ArX \rightarrow ArY + ArX^-\cdot \qquad (M3)$$

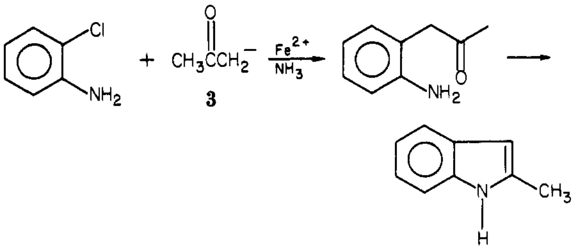
Although this mechanism occasionally is spontaneously initiated, it generally does not occur unless "switched on" through action by the chemist. Photostimulation is often effective, as is initiation by supplying electrons either as solvated electrons[2] or from a cathode.[3] Each of these methods of provocation suffers disadvantages in certain circumstances.

We now report that iron(II) salts effectively catalyze what appear to be aromatic $S_{RN}1$ reactions. Thus bromobenzene (29 g) and excess pinacolone enolate ion (**1**) in ammonia solution react during 75 min in the dark to form 1-phenyl-3,3-dimethyl-2-butanone (**2**) in 58% yield (eq 1)

$$PhBr + \underset{\mathbf{1}}{Me_3CC(O)CH_2^-} \xrightarrow[NH_3]{Fe^{2+}} \underset{\mathbf{2}}{PhCH_2C(O)CMe_3} + Br^- \qquad (1)$$

in the presence of $FeSO_4$ (15 mol % with respect to PhBr) but fail to react if the iron salt is absent. Iodobenzene gives a higher yield, 87% (isolated and weighed). Acetone enolate ion (**3**) reacts similarly forming phenylacetone (**6**). Details appear in Table I.

It is noteworthy that this principle of catalysis is also effective in the reaction[4] of *o*-chloroaniline with **3** to form 2-methylindole in 51% yield (eq 2).



(2)

Another nucleophile well-behaved in aromatic $S_{RN}1$ reactions is diethyl phosphite ion (**4**);[2] see eq 3. It reacts

$$PhI + \underset{\mathbf{4}}{(EtO)_2PO^-} \xrightarrow[NH_3]{Fe^{2+}} \underset{\mathbf{5}}{PhP(O)(OEt)_2} + I^- \qquad (3)$$

with iodobenzene in the dark under iron(II) catalysis to form 98% of diethyl phenylphosphonate (**5**) in 20 min time and even 48% of **5** in 1 min. As when reaction is photostimulated,[5] PhBr reacts less satisfactorily with **4**.

Reaction of PhI with a mixture of **1** and **4** was faster when provoked by $FeSO_4$ (Table I, run 9) than by Pyrex-filtered irradiation in our Rayonet photochemical reactor. However, the relative reactivity of the two nucleophiles (**4** being 1.4 times as reactive as **1**) was the same as under photostimulation.[6] This observation strongly suggests that the same intermediate reacts with the nucleophiles in both systems, and supports assignment of the $S_{RN}1$ mechanism to these reactions.

The efficacy of various iron species as catalysts was explored. In reaction with a mixture of **1** and **4**, hydrated ferrous sulfate was much less effective than the thoroughly dried salt.[7] Iron(III) salts showed little catalytic activity, nor did iron(II) chelated with acetylacetone. Also ineffective was whatever low-valent iron species is formed by reduction of $Fe(NO_3)_3$ with potassium in ammonia (run 14). Also rather ineffective, in lieu of iron(II) salts, were CuCl (run 11) and $SnCl_2$ (run 18). As solvent, dimethyl sulfoxide served reasonably well with catalyst $FeCl_2$ (runs 16 and 17).

Attempts to observe iron(II) catalysis of reactions of PhI with the conjugate bases of phenol and diethyl malonate were unsuccessful. These nucleophiles are generally unreactive in aromatic $S_{RN}1$ systems.[2]

Because of mentioned analogies with recognized $S_{RN}1$ processes, we think that these iron(II)-catalyzed reactions

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[1] We gratefully acknowledge support of this research by the donors of the Petroleum Research Fund, administered by the American Chemical Society, and by the National Science Foundation.

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[4] Bard, R. R.; Bunnett, J. F. *J. Org. Chem.* **1980**, *45*, 1546.

[5] Bunnett, J. F.; Traber, R. P. *J. Org. Chem.* **1978**, *43*, 1867.

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[7] Salts were dried 6 h under vacuum over P_2O_5 in a drying pistol heated by refluxing toluene.

0022-3263/84/1949-3041$01.50/0

Table I. Cation-Stimulated $S_{RN}1$ Reactions[a]

run	substrate	nucleophile	salt (%)[b]	solvent	time	product	yield,[c] %
1	PhBr	1	$FeSO_4$ (15)	NH_3	75 min	2	58[d]
2	PhBr	1	$FeSO_4$ (50)	NH_3	90 min	2	67
3	PhI	1	$FeSO_4$ (15)	NH_3	20 min	2	87[d]
4	*o*-chloroaniline	3	$FeSO_4$ (34)	NH_3	4 h	2-methylindole	51[d]
5	PhI	4	$FeSO_4$ (15)	NH_3	20 min	5	98
6	PhI	4	$FeSO_4$ (15)	NH_3	1 min	5	48
7	PhBr	4	$FeSO_4$ (15)	NH_3	75 min	5	0.3
8	PhBr	4	$FeSO_4$ (100)	NH_3	60 min	5	4
9	PhI	1 and 4	$FeSO_4$ (15)	NH_3	12 s	2 plus 5	93
10	PhI	1 and 4	photostim.[e]	NH_3	12 s	2 plus 5	50
11	PhI	1 and 4	CuCl (15)	NH_3	5 min	2 plus 5	13
12	PhI	1 and 4	$Fe_2(SO_4)_3$ (15)	NH_3	5 min	2 plus 5	1.4
13	PhI	1 and 4	$FeSO_4{\cdot}7H_2O$ (15)	NH_3	12 s	2 plus 5	44
14	PhI	4	$Fe(NO_3)_3$/K (22)	NH_3	1 min	5	2
15	PhI	4	$Fe(AcAc)_2$ (13)	NH_3	1 min	5	1
16	PhI	3	$FeCl_2$ (17)	Me_2SO	10 min	6	60
17	PhI	3	$FeCl_2$ (55)	Me_2SO	4 min	6	65
18	PhI	3	$SnCl_2$ (35)	Me_2SO	10 min	6	5

[a] Reactions were run in the dark at −33 °C in NH_3 or at 25 °C in Me_2SO by employing generally 4 mmol of substrate and a 3- to 6-fold excess of nucleophile in 100 mL of solvent. Sublimed *t*-BuOK was used to generate the anions. [b] Percentage of dry salt respect to the substrate. [c] From GLC analysis and titration of the halide released, unless otherwise noted. The retention time of the products matched those of pure authentic samples and an internal standard calibration was used to reckon the yields. [d] Isolated and weighed. [e] From ref 6.

occur by that mechanism. The function of the iron catalyst is however unclear. Conceivable are electron transfer from Fe^{2+} to PhI and iron-mediated electron transfer from nucleophile to PhI, to generate the radical anion that reacts in step M1, Scheme I. Also conceivable is direct capture of iodine from PhI, as in step M4, to form the radical that

$$\mathrm{PhI} + \mathrm{Fe}^{2+} \rightarrow \mathrm{Ph}\cdot + \mathrm{FeI}^{2+} \qquad \text{(M4)}$$

reacts in step M2. Although these steps may be thermodynamically disfavored, and therefore slow, they may occur sufficiently to initiate the mechanism which then persists because the propagation cycle is efficient.

Despite some evidence favoring $S_{RN}1$, we cannot entirely rule out organometallic mechanisms involving, say, a phenyliron intermediate.

Superficially these reactions bear some resemblance to the well-known aromatic nucleophilic displacements catalyzed by copper(I) salts.[8] However, certain features of the latter, especially their operation with nucleophiles that are ineffective in proper aromatic $S_{RN}1$ reactions, such as hydroxide, phenoxide, and diethyl malonate conjugate base anions, suggest that they do not occur by the $S_{RN}1$ mechanism. We think the iron(II)- and copper(I)-catalyzed reactions to be of different character.

It is possible that this principle of iron catalysis will be of substantial value in preparative use of $S_{RN}1$ reactions.

Registry No. 1, 64723-95-1; 2, 6721-67-1; 3, 24262-31-5; 4, 29800-93-9; 5, 1754-49-0; PhBr, 108-86-1; PhI, 591-50-4; *o*-$ClC_6H_4NH_2$, 95-51-2; $FeSO_4$, 7720-78-7; CuCl, 7758-89-6; $Fe_2(SO_4)_3$, 10028-22-5; K, 7440-09-7; $Fe(AcAc)_2$, 14024-17-0; $FeCl_2$, 7758-94-3; $SnCl_2$, 7772-99-8; Fe^{2+}, 15438-31-0; 2-methylindole, 95-20-5.

Carlo Galli, J. F. Bunnett*

Department of Chemistry
University of California
Santa Cruz, California 95064

Received April 9, 1984

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(8) Bacon, R. G. R.; Hill, H. A. O. *Q. Rev. Chem. Soc.* **1965**, *19*, 95.

(9) Typical experimental procedure: Ammonia (50 mL) was distilled from sodium into a three-necked flask flushed with N_2 and equipped with a cold-finger type condenser (with 2-propanol and solid CO_2 in the coolant well) and a serum cap. The glassware had been flamed in a stream of nitrogen. Under magnetic stirring, 4.5 g of freshly sublimed *t*-BuOK and 300 mg of dried $FeSO_4$ were added through paper funnels. The color of the solution became green-gray. Pinacolone (3.8 g) was added from a syringe and after few minutes also PhI (2.6 g) was added from a syringe. This marked the beginning of the reaction. The flask was kept under magnetic stirring in a dark hood for 20 min, and then NH_4NO_3 was added to quench the reaction. A rusty color developed; after evaporation of ammonia, water was added and the mixture was extracted with ether, washed with water, and dried over Na_2SO_4. Removal of the solvent left a yellow liquid which was distilled (bp 98 °C at 2 mmHg) to give 1.9 g of colorless liquid 2 (85% yield).