Homogeneous Catalyzed Reduction of Nitro Compounds. IV. Selective and Sequential Hydrogenation of Nitroaromatics

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Received November 14, 1975

Dichlorotris(triphenylphosphine)ruthenium(II) and related iron and ruthenium complexes have been found to catalyze the selective homogeneous hydrogenation of nitroaryls to amines. Certain of the ruthenium complexes, exemplified by $RuCl_2(PPh_3)_3$, are highly specific; dinitroaromatics may be reduced to the intermediate nitro amines in good yields, and in the presence of a second mononitroaromatic component, nitro amine synthesis may be carried out to the substantial exclusion of mononitroaromatic hydrogenation and diamine formation. Sequential hydrogenation has been demonstrated also for certain alkylated nitroaromatics, including mixtures of nitroxylene isomers, and nitropolyaromatics in the presence of nitromonoaromatics. Other functional groups such as halogen, hydroxide, alkoxide, ester, and nitrile may also be present without suffering transformation during $C-NO_2$ hydrogenation. Possible mechanisms of this multistep homogeneous reduction are discussed in relation to the observed kinetics, and the scope of the sequential hydrogenation technique as it is affected by both the electronic and steric properties of the substrates and catalysts.

Although a variety of heterogeneous catalysts already exist for the catalytic hydrogenation of nitroaromatic substrates (e.g., Adams' catalyst, Raney nickel, and copper chromite[1]), the purpose of this work was to develop novel homogeneous hydrogenation catalysts possessing unique selectivity properties not found in their heterogeneous counterparts. The intrinsic high degree of selectivity characteristic of homogeneous catalysts is now well recognized,[2,3] but this aspect of homogeneous $C-NO_2$ hydrogenation has, for the most part, been overlooked.[4] We have described in a previous paper the application of dichlorotris(triphenylphosphine)ruthenium(II), and related complexes, to the hydrogenation of nitroparaffins to secondary alkyl primary amines.[5] An improved performance for this complex is reported here for the hydrogenation of nitroaromatics (eq 1).[6]

$$PhNO_2 + 3H_2 \rightarrow PhNH_2 + 2H_2O \quad (1)$$

Selective reduction of a variety of nitroaromatic substrates has been carried out at $PhNO_2$/Ru mole ratios of 200 or more, in neutral, basic, and acidic media, at ambient temperatures or above, and superatmospheric H_2 pressures. Other catalyst precursors include $[RuCl_2(CO)_3]_2$, $RuCl_2(CO)_2(PPh_3)_2$, and related complexes of ruthenium and iron. The uniqueness of certain of the ruthenium complexes lies not only in their ability to selectively hydrogenate variously substituted mono- and dinitroaromatics, but also their ability to sequentially reduce mixtures of two or more classes of nitroaromatic, to the substantial exclusion of other fractions.[7] Sequential hydrogenation is exemplified herein for mixtures of alkylated nitroaromatics, mixtures of nitrobinuclear and mononuclear aromatics, and mixtures of mononitroaromatics with dinitroaromatics.

Experimental Section

Materials. Hydrogen (prepurified grade) and deuterium (technical grade) were purchased from the Matheson Co.; dichlorotris(triphenylphosphine)ruthenium(II), dichlorotricarbonylruthenium(II) dimer, ruthenium acetylacetonate, iron pentacarbonyl, and iron naphthenate were also commercial samples; tricarbonylbis(triphenylphosphine)iron,[8] tricarbonylbis(triphenylarsine)iron,[8] and dichloro(dicarbonyl)bis(triphenylphosphine)ruthenium(II)[9] were prepared by the published methods. Nitrobenzene was redistilled prior to use; all other nitroaromatics were commercial samples and were used as received.

Synthesis Procedure. All syntheses of aromatic amines were carried out under superatmospheric pressures of H_2 in a glass-lined "autoclave" pressure reactor of 300-ml capacity, fitted with mechanical stirring, and linked to a temperature controller and recorder and a pressure gauge.

A known weight of iron or ruthenium complex (0.1–1 mmol) is dissolved, with stirring, in a 100-ml sample of predried N_2-saturated equivolume benzene–ethanol mixture containing 10–100 mmol of nitroaromatic, alkali-metal hydroxide is added as required, and the mixture transferred to the pressure reactor. Hydrogenation is carried out under a constant pressure of hydrogen (20–100 atm), while heating to temperature (25–150 °C) for 1–6 h. On cooling, the product liquid is concentrated under reduced pressure, and the amine product isolated by ether extraction. The aromatic amines are identified by ir, NMR, and by comparison with authentic samples. A typical synthesis of 2,6-xylidine from 2-nitro-*m*-xylene, catalyzed by $RuCl_2(PPh_3)_3$, gave the following results: material balance, 101%, conversion of 2-nitro-*m*-xylene, 98%, yield of isolated 2,6-xylidine, 81 mol %. Anal. Calcd for $C_6H_3(CH_3)_2NH_2$: C, 79.3; H, 9.15; N, 11.55. Found: C, 79.0; H, 9.4; N, 11.4.

Sequential Hydrogenation. Sequential hydrogenation experiments were also carried out in the 300-ml "autoclave" pressure reactor described above. Dichlorotris(triphenylphosphine)ruthenium(II) (0.1–0.5 mmol) is dissolved in a predried, N_2-saturated mixture of benzene (45 ml) and ethanol (50 ml), and the red solution heated to temperature under a moderate pressure of hydrogen (5–10 atm) in the pressure reactor. A mixture of two or more nitroaromatics (10–100 mmol each) in 5 ml of benzene is then injected from a side ampule into the reaction mix, and the pressure of hydrogen adjusted to 40–100 atm. The course of reduction to amine is monitored by withdrawing small (1–2 ml), clear, yellow liquid samples at regular time periods, and analyzing them by GLC. Once the pattern of sequential hydrogenation of a particular nitroaromatic substrate mixture has been established, hydrogenation may be arrested at the appropriate time by rapid cooling of the reactor, and by removal of the hydrogen. The product amines may be isolated by solvent extraction.

Results

General Synthesis. Various soluble ruthenium and iron complexes have been screened for nitroaromatic hydrogenation,[6] particularly those complexes known to catalyze homogeneous hydrogenation reactions,[2-4] and/or transformations of the $C-NO_2$ function.[4,10] Dichlorotris(triphenylphosphine)ruthenium(II) proved to be an excellent catalyst for the selective reduction of $PhNO_2$ to amine (see Table I) even at initial substrate/catalyst mole ratios of 200 or more. Ruthenium carbonyl complexes like $RuCl_2(CO)_2(PPh_3)_2$ show comparable activity; the dimeric $[Ru(CO)_3Cl_2]_2$ complex, lacking organophosphine ligands, undergoes some degradation to the metal (expt 3). Related complexes of iron(II), such as $FeCl_2(PPh_3)_2$, are unsuitable because of their extreme lability, particularly in hydroxylic solvents.[11] The more stable phosphine substituted iron(0) carbonyls, like $Fe(CO)_3(PPh_3)_2$, that are known to undergo a variety of oxidative-elimination reactions,[12] proved more promising (expt 6), and upon conclusion of the reduction, crystalline $Fe(CO)_3(PPh_3)_2$ may be recovered unchanged.

Table I. Nitrobenzene Hydrogenation in the Presence of Various Iron and Ruthenium Complexes[a]

Expt	Catalyst composition	Registry no.	Reaction time, min	Nitrobenzene conversion, %	Aniline selectivity, %
1	$RuCl_2(PPh_3)_3$	15529-49-4	420	>99	90
2	$RuCl_2(PPh_3)_3$[b]		200	99	89
3	$(RuCl_2(CO)_3)_2$[c]	25594-69-0	220	>99	85
4	$RuCl_2(CO)_2(PPh_3)_2$	14564-35-3	420	>99	96
5	$Ru(CH_3COCHCOCH_3)_3$[c]	14284-93-6	240	24	95
6	$Fe(CO)_3(PPh_3)_2$	14741-34-5	500	>99	87
7	$Fe(CO)_3(AsPh_3)_2$[c]	14375-85-0	180	>99	94
8	$Fe(CO)_5$[c]	13463-40-6	420	31	>95
9	$Fe(naphthenate)_3$	1338-41-3	240	7	>90

[a] Run conditions: 1.6 mM [Ru] or [Fe]; 0.32 M $PhNO_2$; 125°C; 80 atm H_2; benzene–ethanol (1:1) solvent. [b] 3.0 mM [Ru], 0.30 M $PhNO_2$; 135 °C. [c] Some catalyst decomposition during these runs as evidenced by the precipitation of insoluble ruthenium or iron species.

Table II. Nitrobenzene Hydrogenation Catalyzed by $RuCl_2(PPh_3)_3$ in Various Solvent Media

Expt	Solvent media	$[PhNO_2]/[Ru]$ ratio	Reaction: Temp, °C	Reaction: H_2 pressure, atm	Reaction: Time, min	Nitrobenzene conversion, %	Aniline selectivity, mol %
10	Benzene–ethanol–KOH[a]	200	130	89	45	>99	96
11	Benzene–ethanol–KOH	50	25	82	570	>99	95
12	Benzene–ethanol–KOH	50	25	20	570	35	78
13	Benzene–ethanol–KOH	50	25	1	460	<5	76
14	Benzene–ethanol[b]	200	130	80	420	>99	89
15	Benzene	200	120	82	300	30	>99
16	Benzene–ethanol–acetic acid[c]	200	135	82	250	>99	92

[a] Run conditions: 3.6 mM $RuCl_2(PPh_3)_3$; 0.14 M KOH; benzene–ethanol (5:2 v/v). [b] 3.0 mM $RuCl_2(PPh_3)_3$; benzene–ethanol (1:1 v/v). [c] 5% (v/v) concentrated glacial acetic acid.

Although $Fe(CO)_3(PPh_3)_2$ is generally less effective than $RuCl_2(PPh_3)_3$ and related ruthenium complexes (cf. expt 1–6), it is considerably more active than iron pentacarbonyl in this application. Bis(triphenylphosphine)tricarbonyliron(0), on the other hand, which more readily undergoes initial dissociation,[3,12] and which shows greater specific activity (expt 7), is also subject to degradation during the $PhNO_2$ reduction, as evidenced by the formation of insoluble iron hydroxyl species. Analogous iron and ruthenium complexes have been found active for both the sequential hydrogenation of nitroaromatics (see below), and for the reduction of nitroaliphatics.[5]

Effect of Reaction Parameters. Dichlorotris(triphenylphosphine)ruthenium(II), the standard catalyst precursor in much of this work, is readily soluble in 1:1 benzene–ethanol,[13] and hydrogenation proceeds under these conditions to give aniline, and other aromatic amines, in at least 85 mol % selectivity (expt 14, Table II). The stoichiometry of eq 1 is confirmed by Karl Fischer titrations. *N*-Ethylaniline is a major by-product from nitrobenzene reduction, together with trace amounts of *N,N*-diethylaniline. Hydrogenation is generally more rapid in alkali-treated benzene–ethanol, and even at nitrobenzene/Ru molar ratios of 200, reduction may be completed within 1 h (expt 10). Furthermore, aniline is produced in near-quantitative yields. The enhanced activity of $RuCl_2(PPh_3)_3$ by base additives has been noted previously for the selective hydrogenation of certain 3-oxo-1,4-diene steroids.[14] In both cases, the improved activity may be attributed to the base-promoted formation of intermediate ruthenium–hydride complexes such as that depicted in eq 2.[15]

$$RuCl_2(PPh_3)_3 + H_2 + \text{base} \rightleftharpoons RuHCl(PPh_3)_3 + \text{base}\cdot HCl \quad (2)$$

In the absence of alkali, the ethanol cosolvent, or the aromatic amine product, may serve as less effective promoters of the hydride formation step. This is consistent with considerably slower hydrogenation rates in benzene alone (expt 15), and similar rates for $RuCl_2(PPh_3)_3$ and $RuHCl(PPh_3)_3$ in benzene–ethanol.[5] The addition of organic acids, in the form of a 5% concentration of glacial acetic acid, does not significantly alter the aniline selectivity (cf. expt 14 and 16), and there is no evidence for *p*-aminophenol, such as might be generated if phenylhydroxylamine were involved in the reduction sequence.[16]

The development of accurate kinetic data for reaction 1 has been hampered by the poor reproducibility of the rate measurements, and induction periods at high $(PhNO_2)/(Ru)$ ratios. The poor reproducibility may be due to the extreme sensitivity of the catalyst solutions to dissolved oxygen,[13,17] the use of mixed solvent media, and the effect of the amine products, which are known to complex directly with ruthenium(II)–triphenylphosphine complexes,[18] and to shift the equilibria (2). Initial rate studies, designed to minimize the effects of the aniline product, were found to obey a first-order dependence upon ruthenium catalyst concentration over the range 1.0–5.0 mM [Ru] at moderate $[PhNO_2]/[Ru]$ ratios of ca. 100. The apparent faster rates at lower [Ru] are indicative of increased dissociation of the $RuHCl(PPh_3)_3$ complex[19] and/or the possible importance of more than one catalytically active species.[20,21] It has been estimated[22] that at 25 °C, K (eq 3) $< 10^{-5}$, but more extensive dissociation is likely at 100–130 °C owing to thermal stimulation.

$$RuHCl(PPh_3)_3 \rightleftharpoons RuHCl(PPh_3)_2 + PPh_3 \quad (3)$$

Consistent also with this displacement of ligand from $RuHCl(PPh_3)_3$, we find a small inverse dependence of the rate upon added PPh_3. In comparative experiments, the addition of a two molar excess of PPh_3 ([Ru] = 2 mM) resulted in a 45% drop in reaction rate, and slower rates with further quantities of PPh_3.

Figure 1[38] shows how the measured rate varies linearly with applied H_2 pressure. Rates of deuteration are slower, with a kinetic isotope ratio (k_H/k_D) of 1.47; this is in spite of competing D_2–ethanol exchange. Amine formation is extremely slow under ambient conditions (Table II, expt 13) and in contrast to the rapid hydrogenation of 1-alkenes

Table III. Hydrogenation of Substituted Nitroaromatics[a]

Expt	Nitroaromatic	Registry no.	Nitroaromatic conversion, %	Major products: Identity	Major products: Selectivity, mol %
17	*p*-Nitrotoluene	99-99-0	84	*p*-Toluidine	92
18	4-Nitro-*o*-xylene	99-51-4	79	3,4-Xylidine	81
19	2-Nitro-*m*-xylene	81-20-9	63	2,6-Xylidine	92
20	1-Nitronaphthalene	86-57-7	65	1-Aminonaphthalene	91
21	1-Chloro-4-nitrobenzene	100-00-5	99	4-Chloroaniline	89
22	1-Bromo-4-nitrobenzene	586-78-7	99	4-Bromoaniline	67
23	4-Nitrophenol	100-02-7	99	*p*-Aminophenol	96
24	4-Nitroanisole	100-17-4	91	*p*-Anisidine	81
25	*p*-Nitrobenzonitrile	619-72-7	77	*p*-Aminobenzonitrile	78
26	2-Nitrothiophene	609-40-5	<1		
27	5-Nitroquinoline	607-34-1	99	5-Aminoquinoline	51
28	*w*-Nitrostyrene	103-64-0	17[b]	2-Phenylnitroethane	>80
29	Ethyl *p*-nitrocinnamate	953-26-4	42[c]	Ethyl *p*-nitro-2-phenylpropionate Ethyl *p*-amino-2-phenylpropionate	83 14

[a] Standard run conditions: 2.5 mM $RuCl_2(PPh_3)_3$; 0.25 M $PhNO_2$; 135 °C; 80 atm H_2; 300 min. [b] Run at 25 °C for 24 h. [c] Run at 105 °C for 120 min.

under subatmospheric pressures of hydrogen,[13] only upon going to superatmospheric H_2 pressures is it possible to generate aniline at reasonable rates (expt 11).

Hydrogenation of Substituted Nitroaromatics. Selective C–NO_2 hydrogenation by $RuCl_2(PPh_3)_3$ has been demonstrated in the presence of a variety of substituent groups, including chloride, bromide, hydroxide, alkoxide, alkyl, aryl, and ester groupings (see Table III). No reduction was detected with S heterocyclics such as 2-nitrothiophene (expt 26), but 5-aminoquinoline was obtained in 51% yield from 5-nitroquinoline. This constrasts with the reported deactivation of $RuHCl(PPh_3)_3$ by pyridine and its derivatives in the case of alkene hydrogenation[13] and the formation of isolable complexes with heterocycles like 2,2′-bipyridyl.[13,23]

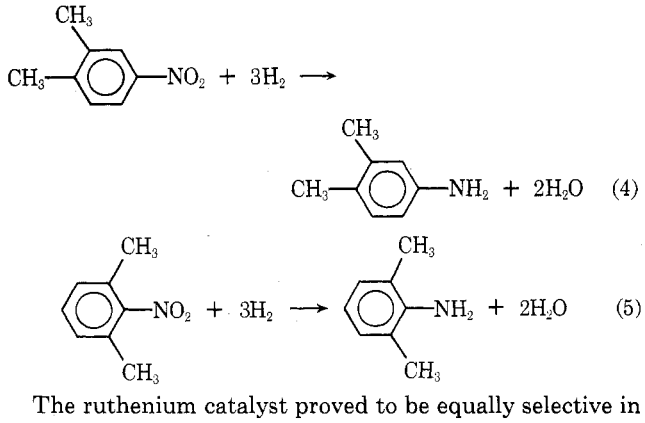
Since $RuCl_2(PPh_3)_3$ is well recognized as a catalyst precursor for selective alkene hydrogenation,[13,19] it was of interest to examine the performance of the complex with certain nitro olefins. Two nitro olefins were considered under standard hydrogenation conditions (see Table III). Reduction of ethyl *p*-nitrocinnamate takes place in two distinct steps. The initial reaction is reduction of the unsaturated carbon–carbon double bond to give ethyl *p*-nitro-2-phenylpropionate, and only after some 35% of the *p*-nitrocinnamate ester has reacted is a second reduction step, of the *p*-nitro group to amine, in evidence. The final product is ethyl *p*-amino-2-phenylpropionate.

ω-Nitrostyrene is subject to rapid polymerization under similar conditions, and in the presence of alkali, but at ambient temperatures, selective reduction to 2-phenylnitroethane has been observed (expt 28); small quantities of fully reduced phenethylamine were also detected. Nitronitriles such as *p*-nitrobenzonitrile lead to moderate yields of the corresponding aminonitrile, with only minor amounts of diamine.

For certain of the para-substituted nitroaromatics listed in Table III, the initial rates of hydrogenation have been measured under standard conditions, and a linear plot of the logarithm of their relative rates vs. Hammett's substituent constants is shown in Figure 2.[38]

Generally an increase in the electron-withdrawing capability of the para substituent (i.e., H → NO_2) is paralleled by an increase in hydrogenation rate. Conversely, electron-donating substituents, which tend to increase the electron density on the nitro function, and thereby lower the polarization of the N–O bonds,[24,25] lead to slower rates of hydrogenation.

Sequential Reduction of Nitroaromatic Mixtures. In order to fully explore possible areas of novelty for the $RuCl_2(PPh_3)_3$ catalyst, the course of C–NO_2 reduction has been followed in a series of competitive experiments with mixtures of variously substituted nitroaromatics. In the first experimental series, equimolar mixtures of certain alkylated nitrobenzenes were subjected to $RuCl_2(PPh_3)_3$ catalyzed hydrogenation to determine if the ruthenium catalyst would preferentially act upon particular classes of structure. Two sets of experiments exemplifying a sequential hydrogenation technique are illustrated in Figures 3 and 4. Figure 3 shows the case for an equimolar charge of two nitroxylene isomers, 4-nitro-*o*-xylene and 2-nitro-*m*-xylene; the initial reaction is preferential reduction of the 4-nitro-*o*-xylene isomer to 3,4-xylidine (eq 4), and only after some 90% of this material has been reduced to amine is any significant quantity of the 2-nitro-*m*-xylene converted to 2,6-xylidine (eq 5).



The ruthenium catalyst proved to be equally selective in the case of equimolar mixtures of nitromesitylene and nitrobenzene (Figure 4).[38] Here, at least 95% of the nitrobenzene is hydrogenated to aniline prior to reduction of the nitromesitylene to mesidine.

The two cited examples of sequential hydrogenation do, of course, represent particular circumstances where one nitroaromatic component has both ring positions ortho to the nitro group filled by alkyl groups, whereas the second component has no ortho substituents. Even so, with other two-component mixtures where, for example, one component has two ortho substituents and the other has only one (e.g., mixtures of 4-nitro-*m*-xylene and 2-nitro-*m*-xylene), then sequential hydrogenation is still possible with the $RuCl_2(PPh_3)_3$ catalyst (see Table IV). Generally, to ensure sequential hydrogenation of alkylated nitrobenzene mixtures with this class of catalyst, it is necessary only that at

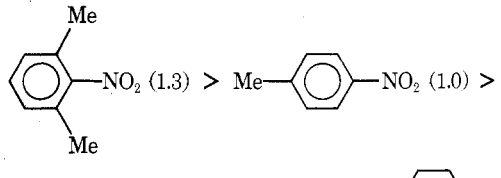
Table IV. Sequential Hydrogenation of an Equimolar Nitroxylene Mixture[a]

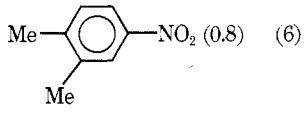
Time from start of hydrogenation, min	Conversion of 4-Nitro-*m*-xylene to 2,4-xylidine, mol %	Conversion of 2-Nitro-*m*-xylene to 2,6-xylidine, mol %
15	13	<1
30	27	<1
45	39	2
60	50	4
90	75	11
120	>99	22
180	>99	50
240	>99	76
300	>99	98

[a] Run conditions: 4.0 mM $RuCl_2(PPh_3)_3$; 0.20 M; $C_8H_9NO_2$; 125 °C; 80 atm H_2.

least one component be disubstituted ortho to the NO_2 function. It is only where there is no diortho substitution, as in the case of mixtures of 4-nitro-*o*-xylene and 4-nitro-*m*-xylene, that the $RuCl_2(PPh_3)_3$ fails to discriminate.

The unique selectivity exemplified here for $RuCl_2(PPh_3)_3$-catalyzed nitroaromatics hydrogenation is in some ways akin to the selective hydrogenation of alkene–alkyne mixtures.[26] In both applications, the observed sequential hydrogenation is likely the result of preferential complexation with the ruthenium catalyst ($K_{\text{substrate 1}} > K_{\text{substrate 2}}$) rather than due to the kinetic effect of marked differences in the hydrogenation rates ($k_{\text{substrate 1}} < k_{\text{substrate 2}}$).[19] Certainly in the case of alkylated nitrobenzenes, both hindered and nonhindered, we find the individual rates of hydrogenation to vary by less than a factor of 2 in the order of eq 6 (relative rates in parentheses).





(6)

On the other hand, in competitive experiments with mixtures of substituted nitrobenzenes, as described above, there is little or no reduction of the ortho-substituted components during the course of reduction of the less sterically crowded derivatives.

Sequential Hydrogenation of Nitroaromatic–Nitrobinuclear Aromatic Mixtures. Competitive experiments designed to determine the effect of a second phenyl ring adjacent to the nitro function[27,28] have served to demonstrate that (a) with an equimolar 1-nitronaphthalene–nitrobenzene mixture, the $RuCl_2(PPh_3)_3$ solutions are selective for 1-nitronaphthalene hydrogenation only up to about 30% conversion, beyond 30% both substrates are reduced concurrently, and (b) with an equimolar mixture of 1-nitronaphthalene and the sterically hindered 2-nitromesitylene, reduction of the nitronaphthalene to α-napthylamine is essentially complete (>95% conversion) before nitromesitylene reduction to mesidine gets under way. Other ruthenium complexes, including $RuCl_2(CO)_2(PPh_3)_2$ and $RuCl_2(SbPh_3)_3$, display similar selectivity patterns, but analogous iron complexes proved nonselective under these conditions.

Selective Hydrogenation of Dinitroaromatics. The performance of the $RuCl_2(PPh_3)_3$ catalyst is illustrated here for several typical dinitroaromatics, including *m*-dinitrobenzene and *p*-nitrobenzene. The increase in initial rate of nitroaromatic hydrogenation caused by introducing a second para NO_2 substituent has already been noted in Figure 2. The results of a typical run with *p*-dinitrobenzene are reproduced in Figure 5. The initial reaction is selective reduction of the *p*-dinitrobenzene to *p*-nitroaniline (eq 7), and only after 85–90% of the starting dinitro compound has been reduced to the intermediate *p*-nitroaniline is *p*-phenylenediamine (eq 8) detected in the reaction mix.

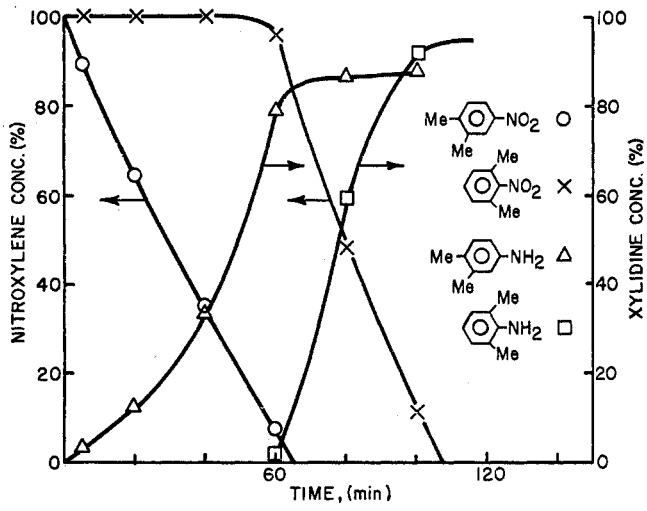


Figure 3. The sequential hydrogenation of equimolar nitroxylene mixture: (a) ○, 4-nitro-*o*-xylene; ×, 2-nitro-*m*-xylene; △, 3,4-xylidine; □, 2,6-xylidine. (b) Run conditions: 5.0 mM $RuCl_2(PPh_3)_3$; 0.26 mM $C_8H_9NO_2$; 135 °C; 80 atm H_2.

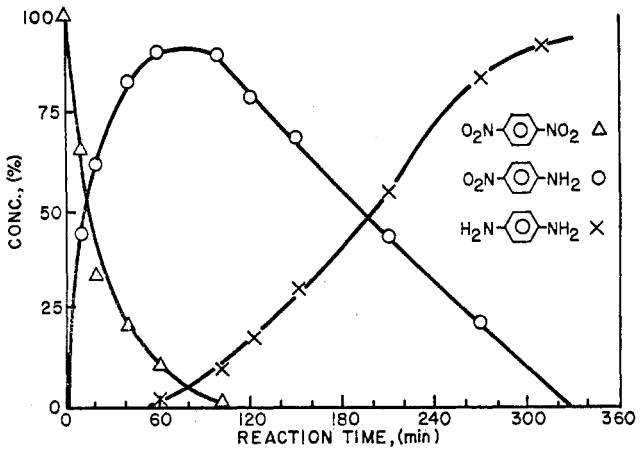
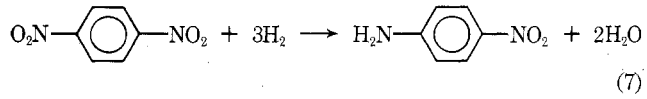


Figure 5. The selective hydrogenation of *p*-dinitrobenzene: (a) △, *p*-dinitrobenzene; ○, *p*-nitroaniline; ×, *p*-phenylenediamine. (b) Run conditions: 2.5 mM $RuCl_2(PPh_3)_3$; 0.25 M $C_6H_4(NO_2)_2$, 135 °C; 80 atm H_2.



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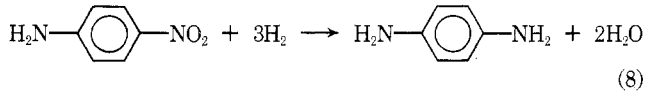
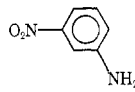
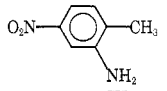
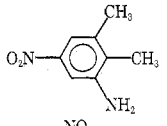
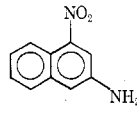


(8)

This high selectivity for the intermediate nitro amine is unusual in the catalytic hydrogenation of nonhindered polynitro compounds.[29] Smith, for example, reports[30] the hydrogenation of polynitroaromatics over Adams' platinum catalyst to proceed without breaks in the kinetic curves. In these experiments (Figure 5), after initial hydrogenation of the *p*-dinitrobenzene, there is expected to be a competition between the *p*-dinitrobenzene and the newly formed *p*-nitroaniline for the available coordination sites on the ho-

Table V. Selective Hydrogenation of Dinitroaromatics[a]

Dinitroaromatic	Registry no.	Reaction time, min	Dinitroaromatic conversion, %	Major product: Identity[b]	Major product: Selectivity, mol %
m-Dinitrobenzene	99-65-0	210	77		73
2,4-Dinitrotoluene	121-14-2	180	42		91
3,5-Dinitro-*o*-xylene	616-69-3	180	59		68
1,3-Dinitronaphthalene	606-37-1	120	95		71

[a] Run conditions: 4.0 mM $[RuCl_2(PPh_3)_3]$; 0.1–0.2 M $[Ph(NO_2)_2]$; 125 °C; 80 atm H_2. [b] Identification by NMR, ir, GLC, and, in some cases, by elemental analyses.

mogenous ruthenium catalyst. The difference then in electron density on the coordinating C–NO_2 groups, due to electron withdrawal by the second *p*-NO_2 of the *p*-dinitrobenzene (σ +0.78) vs. *p*-NH_2 electron donation (σ −0.66),[31] appears to play an important role in ensuring preferential bonding with the dinitro component. The result is the high yield of the partially reduced *p*-nitroaniline.

The relative difference in the resonance effects of the NO_2 and NH_2 group will, of course, be diminished in the case of *m*-dinitrobenzene. Here, under the conditions of Figure 5, the concentration of *m*-nitroaniline reaches only 56% of theoretical, and *m*-phenylenediamine is detected after only 60% of the *m*-dinitrobenzene has been converted. Apparently, the inductive and/or steric influences of the meta NO_2 and NH_2 substituents are insufficiently different to ensure high selectivity for the *m*-nitroaniline intermediate. A combination of both steric and electronic effects are in evidence for dinitrotoluenes, dinitroxylenes, and dinitronaphthalenes (see Table V).

Sequential Hydrogenation of Dinitroaromatic–Nitroaromatic Mixtures. The ability of the homogeneous $RuCl_2(PPh_3)_3$ catalyst to selectively hydrogenate dinitroaromatics to their partially reduced species may be put to advantage where one wishes to sequentially hydrogenate dinitroaromatics in the presence of mononitro materials.[32]

In a typical experiment, an equimolar mixture of *p*-dinitrobenzene (13 mmol) and nitrobenzene (13 mmol) was hydrogenated in benzene–ethanol solution containing 0.25 mmol of $RuCl_2(PPh_3)_3$ under normal operating conditions, and reduction followed by GLC as a function of time. The following reaction sequence was observed (see data in Figure 6).

(1) Initial selective reduction of *p*-dinitrobenzene to *p*-nitroaniline.
(2) Hydrogenation of the nitrobenzene component to aniline.
(3) Hydrogenation of the *p*-nitroaniline intermediate to *p*-phenylenediamine.

It is considered particularly significant that almost all (>90%) of the *p*-dinitrobenzene component is converted to *p*-nitroaniline prior to any significant reduction of the nitrobenzene, but that once the second stage is underway (10–15% $C_6H_5NO_2$ conversion to aniline) reduction of the nitrobenzene and the *p*-nitroaniline intermediate take place concurrently.

From similar studies it is concluded that the technique is applicable to a variety of polynitroaromatic–mononitroaromatic mixtures. Both para and meta dinitroaromatics may be selectively reduced to the substantial exclusion of mononitroaromatic components using other ruthenium complexes,[7] including $RuCl_2(CO)_2(PPh_3)_2$, $RuCl_2(SbPh_3)_3$, and $RuCl_3(PPh_3)_2$. Data for a typical *m*-dinitrobenzene–nitrobenzene mix are summarized in Figure 7.[38] The reaction sequence is as follows.

(1) Initial selective reduction of the *m*-dinitrobenzene to *m*-nitroaniline.
(2) Concurrent hydrogenation of the *m*-nitroaniline and nitrobenzene components to their respective amines.

Again, it is considered significant that reduction of the *m*-dinitrobenzene component is essentially complete (>95% conversion) before there is any detectable reduction either of the nitrobenzene component or the *m*-nitroaniline intermediate.

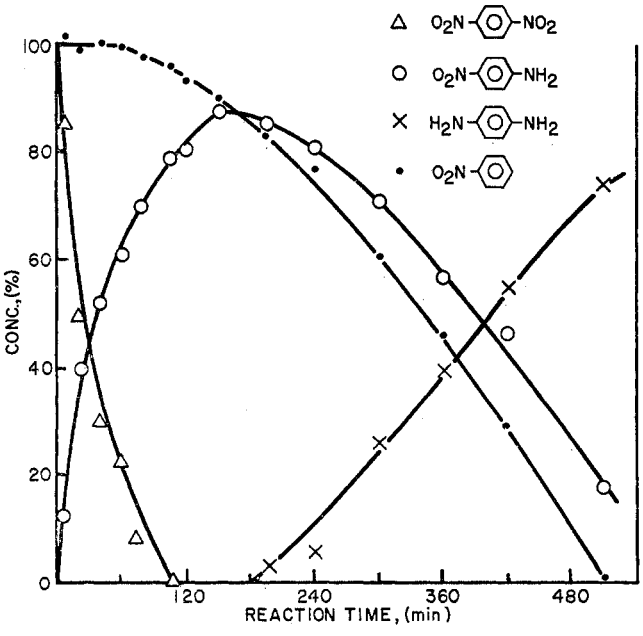


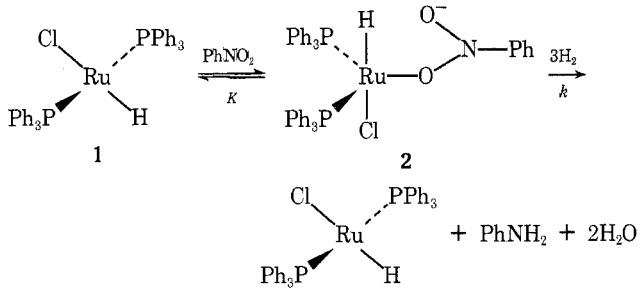
Figure 6. The sequential hydrogenation of an equimolar *p*-dinitrobenzene–nitrobenzene mixture: (a) Δ, *p*-dinitrobenzene; ○, *p*-nitroaniline; ×, *p*-phenylenediamine; nitrobenzene. (b) Run conditions: 2.5 mM $RuCl_2(PPh_3)_3$; 0.13 M $C_6H_4(NO_2)_2$; 0.13 M $C_6H_5NO_2$, 135 °C; 80 atm H_2.

Discussion

The data described above feature the following. (a) The application of homogeneous catalysis to the selective hydrogenation of the C–NO_2 function in a variety of nitroaryls. (b) Techniques for sequentially hydrogenating polynitroaromatics and polynitro–mononitroaromatic mixtures where the ruthenium catalyst appears particularly sensitive to the degree of N–O bond polarization. (c) A method of sequentially hydrogenating certain alkylated nitroaromatic mixtures which may be ascribed to catalyst sensitivity to steric factors, particularly the "ortho" effect.[30]

Extensive studies of hydrogen activation by solutions of the $RuCl_2(PPh_3)_3$ complex[13-15,33-35] have generally been interpreted[36] in terms of initial ruthenium–hydride formation (eq 2) followed by at least partial dissociation to the *trans*-$RuHCl(PPh_3)_2$ complex (1) in accordance with eq 3. Our data (vide supra), particularly the sensitivity of $PhNO_2$ hydrogenation to added base, inhibition by excess ligand, and similar rates for $RuCl_2(PPh_3)_3$ and $RuHCl(PPh_3)_3$ solutions,[5] are in accord with the intermediate formation of 1. Furthermore, the spectra of recovered catalyst samples show ν(Ru–H) at ca. 2020 cm^{-1}. Subsequent interaction of 1 with nitroaryl to yield amine products (Scheme I) likely proceeds via proton transfer and repeated oxidative addition of molecular hydrogen to give octahedral ruthenium(IV)–hydrido species,[19] reductive elimination of amine and the elements of water completing the catalyst cycle. Discrete nitrene species are unlikely to be important in view of the lack of evidence for coupling products,[4b] particularly azo- and hydrazobenzenes, but coordinated nitroso species cannot be discounted since we find the rate of nitrosobenzene reduction to be faster than for nitrobenzene. The sensitivity of the $PhNO_2$ reduction to hydrogen pressure and [Ru] and the small kinetic isotope effect are consistent with oxidative H_2 addition being rate limiting. The fact that no amine is detected in the benzene–ethanol media in the absence of H_2 (see also ref 5) makes it unlikely that ethanol cosolvent is an important alternative hydride source here. This is in spite of recent reports of $RuCl_2(PPh_3)_3$-catalyzed hydrogen transfer.[37] Likewise, $RuHCl(PPh_3)_3$ ortho metalation, which has recently been applied to the stoichiometric reduction of alkenes,[22] is normally slow compared to hydrogenation.[13,22]

Scheme I. Nitroaryl Hydrogenation Catalyzed by $RuHCl(PPh_3)_2$



In spite of the complexities of this catalysis, the unique selectivity data exemplified in Figures 3–7 may be rationalized largely on the basis of competitive substrate interaction with the ruthenium metal center at some stage during the hydrogenation sequence. Similar hydrogenation rates for individual hindered and nonhindered nitroalkylbenzenes (eq 6) point to the relative insensitivity of the slow steps of this catalysis to the bulk of the coordinated nitroaryl molecule, or its partially reduced derivatives. On the other hand, the high selectivity evident during sequential hydrogenation of nitroalkylbenzene mixtures (Figures 3 and 4) suggests widely different complexity constants for the nitroaromatics and ortho-alkylated nitroaromatics bonded to ruthenium in 2 or some latter intermediate, and preferential complexation with the least hindered isomer (e.g., $K_{\text{nitroaromatic}} > K_{\text{nitroalkylaromatic}}$). At least two factors may play a critical role. Firstly, the sterically crowded five coordinate complex 2 accommodates two bulky triarylphosphine ligands, and will therefore bond preferentially with the least sterically hindered nitroaryl substrate available. Secondly, in the case of diortho substituted nitroaryls, such as 2-nitromesitylene and 2-nitro-*m*-xylene, the ortho methyl groups force the nitro group out of the plane of the aromatic ring,[30] thereby preventing free resonance between the aryl and NO_2 functions, and further increasing the effective size of the $PhNO_2$ molecule perpendicular to the plane of the ring.

Steric factors appear to have less influence in the case of sequential polynitroaromatic hydrogenation. The moderate differences in rates for para-substituted nitrobenzenes (Figure 2) point to the degree of polarization of the N–O bonds as significantly affecting the electron density at the metal center in intermediates such as 2, and therefore the ease of rate-determining hydrogenation (i.e., $k_{\text{dinitroaromatic}} > k_{\text{mononitroaromatic}}$). It is unlikely, however, that these differences in rate could, by themselves, account for the observed sequential hydrogenation of dinitroaromatics and dinitro–mononitroaryl mixtures. A second, reinforcing factor would be preferential complexation of the more polar dinitroaromatic components with the catalytically active ruthenium–hydrido species (e.g., 2, $K_{\text{dinitroaromatic}} > K_{\text{mononitroaromatic}}$). Certainly this would be consistent with the improved selectivity observed in hydrogenating para vs. meta dinitrobenzenes (Figure 5, Table V), and with the order of sequential hydrogenation exemplified in Figures 6 and 7.

Acknowledgments. The author thanks Texaco Inc. for permission to publish this paper, and Messrs. T. S. Strothers and C. A. Dondero for experimental assistance.

Registry No.—2,6-Xylidene, 87-62-7; 4-nitro-*m*-xylene, 89-87-2.

Supplementary Material Available. Figures 1, 2, 4, and 7 (4 pages). Ordering information is given on any current masthead page.

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Palladium-Catalyzed Vinyl Substitution Reactions. II. Synthesis of Aryl Substituted Allylic Alcohols, Aldehydes, and Ketones from Aryl Halides and Unsaturated Alcohols

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Received October 7, 1975

A variety of substituted bromo- and iodobenzenes reacted with 2-methyl, 1-methyl, and 1-1-dimethyl allyl alcohols to give aryl substituted aldehydes, ketones, and allyl alcohols, respectively. Bromo- and iodobenzene reacted in a similar manner with some nonallylic unsaturated alcohols. In these cases, the double bond migrated along the carbon chain until captured by the alcohol function to give a carbonyl product. Formation of the intermediate phenyl substituted unsaturated alcohols was minimal unless a quaternary carbon separated the double bond and alcohol functions.

Phenyl substituted carbonyl compounds can be prepared by the palladium-catalyzed reaction of iodobenzene and bromobenzene with allylic alcohols.[1] Heck and co-worker have described a related reaction in which considerable amounts of phenyl substituted unsaturated alcohols were also formed, particularly from the bromo compounds.[2] The reaction was shown to apply to homoallylic alcohols, but again a mixture of products was formed.

In the present paper our work is extended to the reaction of a variety of substituted aryl halides with allylic alcohols and to the reaction of bromobenzene and iodobenzene with some nonallylic unsaturated alcohols. Since the major products were carbonyl compounds even when aryl bromides were used, the reaction has considerable synthetic utility.

Results

Reaction of Substituted Aryl Halides with Allylic Alcohols. The reactions summarized in Table I, parts i and iii, gave predominantly carbonyl compounds as products. Variations in the catalyst and solvent have no special significance, but special conditions were used in some cases to achieve better yields. Where a GC yield is quoted, the product was also isolated and identified in earlier experiments.

Although a wide variety of substituents were tolerated, there were side reactions which appeared to relate to the electron-donating character of the substituent. Thus, the reaction of the 4-nitroiodobenzene gave a 20% yield (isolated) of 4,4′-dinitrobiphenyl which is a fourfold increase over the amount of biphenyl produced from iodobenzene under corresponding conditions.

With electron-donating substituents (OH, OMe, OCH_2O) another side reaction developed, namely reduction of the aryl halide. This occurred in reactions with 1-buten-3-ol, and to a lesser extent with 2-methyl-2-propen-1-ol. This reduction was more significant with the bromide than the iodide and was more pronounced when a tertiary amine was used as base in place of sodium bicarbonate. Thus, in the reaction of 4-iodophenol and 1-buten-3-ol the yields of 4-(4′-hydroxyphenyl)-2-butanone and phenol were 36 and 44%, respectively, when triethylamine was used as base. However, when sodium bicarbonate was used as base with only a catalytic amount of triethylamine, these yields changed to 77 and 2%. In the reaction of 3,4-methylenedioxybromobenzene with methallyl alcohol, methylenedioxybenzene was the sole product when tripropylamine was used as base. However, the use of sodium bicarbonate with or without a catalytic amount of tripropylamine gave yields of approximately 50% of the expected aldehyde.

A further complication was found with 4-alkylbromobenzenes. Although the corresponding iodides reacted satisfactorily, the bromides reacted slowly and palladium metal formed early in the reaction, which stopped at only a partial conversion. A variety of different solvents, bases, and phosphines were tried with 4-*tert*-butylbromobenzene but the best yields were obtained when sodium iodide was used in place of triphenylphosphine. Sodium iodide was used in the hope that halogen exchange might occur to give the 4-*tert*-butyliodobenzene. No evidence for this exchange was found, but the desired product was formed under mild conditions (110 °C) in the absence of phosphine. The reaction rate, conversion, and yield all increased with an increasing amount of the solvent (hexamethylphosphoramide, HMP).