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Kinetics and Mechanism of the Copper(I)-Induced Homogeneous Ullmann Coupling of *o*-Bromonitrobenzene

Theodore Cohen* and Ioan Cristea

Contribution from the Department of Chemistry, University of Pittsburgh, Pittsburgh, Pennsylvania 15260. *Received July 31, 1975*

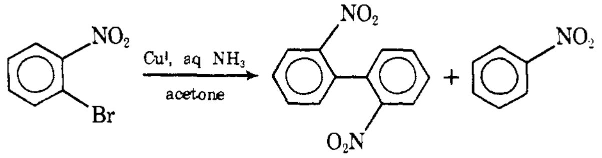
Abstract: A kinetic investigation of the coupling of *o*-bromonitrobenzene to form 2,2′-dinitrobiphenyl in a homogeneous acetone solution containing copper(I) trifluoromethanesulfonate, aqueous ammonia, and acetonitrile has revealed that the reaction is second order in aryl halide and first order in copper(I). The formation of the very minor product, nitrobenzene, is first order in each of these two reactants. Free *o*-nitrophenyl radicals have been excluded as intermediates by the finding that the product distribution is insensitive to the presence of tetrahydrofuran, whereas this additive has the effect of greatly increasing the yield of nitrobenzene when *o*-nitrophenyl radicals are generated in the same media by decomposition of the *o*-nitrobenzenediazonium ion. An organocopper intermediate in the coupling process is indicated by the effect of added ammonium ion which greatly increases the ratio of nitrobenzene to biaryl; the ammonium salt increases the second-order rate constant for production of nitrobenzene but has no appreciable effect on the rate constant for biaryl production. The suggested mechanism, which is completely consistent with these data, involves a reversible oxidative addition of the CBr bond to copper(I) to form an organocopper(III) intermediate which may either displace a bromide ion from a second aryl bromide molecule or become protonated by the medium.

The widely used Ullmann coupling reaction[1-3] produces a biaryl when an aryl halide and copper powder are heated at various temperatures, but frequently in the vicinity of 200°. The mechanism has been extensively reviewed in recent years.[1-4] It now appears agreed[1c,2,4] that the central mechanistic feature is the formation of an organocopper intermediate of unknown oxidation state.[5] However, the exact nature of this intermediate and the processes by which it is formed and consumed remain obscure. From time to time reported experimental results have been interpreted as supporting the presence of radicals during Ullmann coupling,[2,6-8] but none of the evidence is compelling with regard to the actual participation of radicals in the coupling mechanism itself; in fact, the recent finding that iodomaleate and iodofumarate esters couple essentially stereospecifically renders vinyl radicals very unlikely intermediates,[9] and evidence against radical intermediates in the heterogeneous Ullmann coupling of an aryl halide has also been obtained.[10]

In other types of reactions, the mechanistic questions which thus far remain unanswered are usually explored by kinetic studies, but until now these have been impossible owing to the heterogeneous nature of the reaction mixtures. However, the recent discovery[11] of a homogeneous Ullmann reaction performed in organic solvents containing copper(I) trifluoromethanesulfonate (triflate) and aqueous ammonia has now rectified this situation, and we now present the results of a kinetic and mechanistic investigation of this reaction.

Results

Since *o*-iodonitrobenzene couples too rapidly at room temperature for convenient kinetic measurements,[11] a survey was made[12] of the effect of reaction conditions on the product distribution using *o*-bromonitrobenzene, which under the conditions used previously gave *o*-nitroaniline, nitrobenzene, and a low yield of 2,2′-dinitrobiphenyl. It was found that under the conditions described for the kinetic runs in the Experimental Section, a 90% yield of coupling product was formed along with 7.8% of nitrobenzene and about 1% each of *o*-nitrophenol and *o*-nitroaniline; the reaction rate was convenient for following the consumption of aryl halide and the formation of the products.



The kinetic experiments were conducted as follows: copper(I) triflate[13] was prepared under nitrogen by reducing a very slight excess of copper(II) triflate[13] with copper powder in a refluxing solution containing 25 ml of acetone and 1.25 ml of acetonitrile. To this solution at 30° was added a small weighed quantity of copper(II) triflate, which was necessary for an optimum yield of biaryl, 5.0 ml of 20% aqueous ammonia, and a weighed quantity of *o*-bromonitrobenzene. Samples (4 ml) were periodically withdrawn and analyzed gas chromatographically after the addition of a weighed quantity of a standard, 4,4′-dinitrobiphenyl. In all experiments, a large molar excess (at least 10-fold, but in most experiments 20- or 40-fold) of copper(I) triflate was used so that the decrease in the concentration of copper(I) during a kinetic run was essentially negligible; the order in copper(I) during an individual run could thus be assumed to be zero.

Order in Aryl Bromide for the Production of 2,2′-Dinitrobiphenyl. This order was determined by monitoring the decrease in concentration of aryl bromide as a function of time in experiments utilizing two different concentrations of aryl bromide and 5.0 mmol of copper(I). In order to simplify the calculations, it was assumed that biaryl was the only product; this is a good approximation since the biaryl constituted 94.2–96.0% and 95.2–98.0% of the total product during the course of the kinetic study in experiments with initial quantities of aryl bromide of 0.125 mmol and 0.250 mmol, respectively. Data were accumulated in these two experiments until the yields of biaryl were 75 and 82%, respectively. Two tests of the order in aryl bromide were used.

(1) The data for the concentration of aryl bromide as a function of time were fitted by computer to the function $y = a_0 + a_1x + a_2x^2 + \ldots$ using standard regression analysis techniques, and the slope at zero time was determined from the derivative of this equation. For the experiment starting with 0.125 mmol of aryl bromide, a fourth order equation gave the best fit (variance of fit = 0.094) and the initial rate of disappearance of *o*-bromonitrobenzene was 3.34×10^{-7} M s^{-1}; for the experiment starting with 0.250 mmol of aryl bromide, a third order equation gave the best fit (variance = 0.44) and the initial rate was 12.6×10^{-7} M s^{-1}. Thus, doubling of the initial concentration of aryl bromide causes a 3.77-fold increase in coupling rate and a second-order dependence on aryl bromide concentrations is indicated.

(2) This was confirmed when excellent parallel straight lines were obtained by plotting the reciprocal of the concentration of aryl bromide against time utilizing the data from the same experiments. The pseudo-second-order rate constants (k_{obsd}, the actual rate constants would have to be derived from these by dividing by the concentration of copper(I) raised to an appropriate power; see below) were found to be $(2.71 \pm 0.04) \times 10^{-2}$ M^{-1} s^{-1} (correlation coefficient 0.9997) and $(2.70 \pm 0.03) \times 10^{-2}$ M^{-1} s^{-1} (correlation coefficient 0.9995) for the experiments utilizing initial quantities of aryl bromide, respectively, of 0.125 and 0.250 mmol; standard linear least-squares techniques were used to compute these values.

Order in Copper(I) for the Production of Biaryl. This order was ascertained by determining the initial rates of disappearance of aryl bromide in three experiments in which the initial quantity of aryl bromide was held at 0.125 mmol and the initial quantities of copper(I) were 1.25, 2.50, and 5.00 mmol. The initial rates, as determined from the derivatives at zero time of the quadratic equations to which the [ArBr] vs. time data during the first 11 to 20% of the reaction were fitted with variances of fit, respectively, 0.021, 0.21, and 0.021, are 1.03×10^{-7}, 2.03×10^{-7}, and 4.1×10^{-7} M s^{-1}, respectively, for the three concentrations. It is clear that the initial rates are directly proportional to the concentration of copper(I), and the coupling reaction is thus accurately first order in copper(I).

Table I. Effect of Additives on Product Distributions

Substrate[a]	Additive (mmol)	% ArH	% Ar_2	% $ArNH_2$	% ArH/ % Ar_2
ArBr		7.8	89.9	1.2	0.087
ArBr	NH_4BF_4 (2.00)	80.4	16.4	0.9	4.90
ArBr	THF (12.2)	5.8	86.6	0.8	0.067
$ArN_2^+BF_4^-$		26.4	20.6	14.8	1.28
$ArN_2^+BF_4^-$	THF (12.2)	58.5	12.4	14.2	4.72

[a] Ar = *o*-nitrophenyl. The substrate (0.250 mmol) was added to 25 ml of acetone (in the THF experiments, 24 ml of acetone and 1 ml of THF) containing 5.00 mmol of copper(I) triflate, 0.22 mmol of copper(II) triflate, 1.25 ml of acetonitrile, and 5.00 ml of a 20% aqueous ammonia. The reaction times were 24 h for the aryl bromide and 20 min for the diazonium salt.

Order in Aryl Bromide for the Production of Nitrobenzene. In the first experiments described above, the production of the small yield of nitrobenzene was also monitored by gas chromatography. Instantaneous rates of production of nitrobenzene at various times were obtained by plotting the concentration of nitrobenzene against time, for two experiments at two different initial concentrations of aryl bromide, computer-fitting the generated curves to a fourth-order equation (variance of fits 0.005 and 0.0061, respectively), and substituting the times into the first derivative of this equation. Good straight lines (correlation coefficients 0.995 and 0.994) were obtained when these instantaneous rates were plotted against the concentration of *o*-bromonitrobenzene at each of these times. The pseudo-first-order rate constants (the order in copper which was in large excess is discussed below) are $(3.18 \pm 0.13) \times 10^{-6}$ and $(2.81 \pm 0.12) \times 10^{-6}$ s^{-1}, respectively, for initial quantities of aryl bromide of 0.125 and 0.250 mmol. Considering the low yields of nitrobenzene (less than 3.3%) and the errors inherent in determining slopes at individual points on a curve, the agreement of these two rate constants is quite satisfactory.

Order in Copper(I) for the Production of Nitrobenzene. The concentrations of generated nitrobenzene were monitored in two experiments in which the initial aryl bromide concentration was constant (0.125 mmol in 31.25 ml of solvent) and the initial quantity of copper(I) was 1.25 and 5.00 mmol. Initial rates, determined as described above (the variances of the fits were 0.002 and 0.003, respectively), were found to be 0.296×10^{-8} and 1.18×10^{-8} M s^{-1}, respectively. Thus, a 4.00-fold increase in [Cu^{I}] causes a 3.99-fold increase in the initial rate of production of nitrobenzene, and this process, like the production of biaryl, is accurately first order in copper(I).

Effect of Acidity on the Rates and the Distribution of Products. Since the effect of proton sources on Ullmann couplings[1,5,9,10] and other copper-induced reactions of aryl halides[14,15] is to increase the yield of reduction product at the expense of the usual products, the experiment utilizing 5.00 mmol of copper(I) and 0.250 mmol of *o*-bromonitrobenzene was repeated under the usual conditions but in the presence of 2.00 mmol of dissolved ammonium tetrafluoroborate. A sharp increase in the yield of nitrobenzene occurred (Table I). It was further established that this change

Table II. Rate Constants for Formation of Biaryl and Nitrobenzene

Reactants,[a] mmol		$k_{Ar_2} \times 10^{b}$ $M^{-2}\ s^{-1}$	Corr coeff (c) or var of fit (v)	$k_H \times 10^{5\,c}$ $M^{-1}\ s^{-1}$	Corr coeff (c) or var of fit (v)
ArBr	Cu^I				
0.125	5.00	1.69 ± 0.02[d]	0.9997 (c)	1.98 ± 0.08[e]	0.9951 (c)
		1.64[f]	0.094 (v)	1.84[f]	0.003 (v)
0.250	5.00	1.68 ± 0.03[d]	0.9995 (c)	1.76 ± 0.07[e]	0.9940 (c)
		1.62[f]	0.44 (v)	1.76[f]	0.0061 (v)
0.125	5.00	1.60[f]	0.021 (v)		
0.125	2.50	1.59[f]	0.21 (v)		
0.125	1.25	1.61[f]	0.021 (v)		
0.125	1.25			1.90[f]	0.002 (v)
0.250[g]	5.00[g]	1.86 ± 0.09	0.9942 (c)	21.3 ± 0.8	0.9963 (c)

[a] Ar = *o*-nitrophenyl. In 25 ml of acetone, 5.00 ml of 20% aqueous NH_3, and 1.25 ml of CH_3CN. [b] $d[Ar_2]/dt = k_{Ar_2}[ArBr]^2[Cu^I]$. [c] $d[ArH]/dt = k_H[ArBr][Cu^I]$. [d] Obtained by plotting 1/[ArBr] vs. time in an experiment with a large excess of Cu^I. [e] Determined by plotting instantaneous rates (derived by computer curve fitting) vs. [ArBr]. [f] Derived from initial rate. [g] NH_4BF_4 (2.00 mmol) present.

in product distribution is due to a 12-fold increase in the pseudo-first-order rate constant for nitrobenzene production [from $(2.81 \pm 0.12) \times 10^{-6}$ to $(3.40 \pm 0.13) \times 10^{-5}\ s^{-1}$, determined as in the experiments without added ammonium ion from a plot of instantaneous rates against aryl bromide concentration; straight line correlation coefficient 0.996]. In the experiment with added ammonium ion, the rate constant for the formation of the small yield of biaryl could be determined by plotting the biaryl concentration against time, computing the instantaneous rates obtained from the derivative of the curve-fitted equation, and plotting these rates against the square of the aryl bromide concentration; the good straight line (correlation coefficient 0.994) which resulted indicates that biaryl formation is still pseudo-second-order under these conditions and the value of this constant, $(2.98 \pm 0.14) \times 10^{-2}\ M^{-1}\ s^{-1}$, hardly differs from the value, $(2.70 \pm 0.03) \times 10^{-2}\ M^{-1}\ s^{-1}$, determined in the absence of ammonium ion.[16]

Attempted Radical Trappings. In previous work it was shown that tetrahydrofuran (THF) is a far more effective trap for aryl radicals, generated by copper-induced diazonium decomposition, than is acetone.[17] In an attempt to trap possible aryl radical intermediates, the effect on product distribution of replacing 1 ml of acetone with 1 ml of THF in the experiment utilizing 5.00 mmol of copper(I), 0.250 mmol of *o*-bromonitrobenzene, and the standard 4,4′-dinitrobiphenyl was determined. As can be seen (Table I) the added THF has very little effect. There is a slight *decrease* in the ratio of nitrobenzene to biaryl, but this is probably due to the fact that the reaction with THF does not go as far toward completion in 24 h as that without THF; the percent of aryl bromide remaining unreacted is 1.8 with THF and 0.1 without THF (the ratio of nitrobenzene to biaryl produced is far higher toward the end than at the beginning of the reaction).

In order to compare this response toward THF with that of an authentic *o*-nitrophenyl radical,[18] the latter was generated by decomposition of *o*-nitrobenzenediazonium tetrafluoroborate in the same media (with and without THF) as those used in the experiments described just above. The results (Table I) indicate that the presence of the small quantity of THF has a striking effect, increasing the ratio of nitrobenzene to biaryl by a factor of 3.7.

Discussion

Kinetic Order. The kinetic results leave very little doubt that the formation of biaryl is second order in aryl bromide and first order in copper(I), while that of nitrobenzene is first order in each of these reactants:

$$d[Ar_2]/dt = k_{Ar_2}[ArBr]^2[Cu^I] \tag{1}$$

$$d[ArH]/dt = k_H[ArBr][Cu^I] \tag{2}$$

Thus, in the case of biaryl production, the pseudo-second-order constants obtained by plotting 1/[ArBr] against time for individual runs in the presence of a large excess of copper(I) can be converted to third-order constants, k_{Ar_2}, by dividing by $[Cu^I]$, and the initial rates, obtained by following the first part of the reaction, can be converted to k_{Ar_2} by dividing by $[ArBr]^2[Cu^I]$. These derived third-order constants are listed in Table II. The invariance of k_{Ar_2} with changes in the concentration of reactants is quite satisfactory.[16]

In like fashion, the pseudo-first-order rate constants and initial rates for the production of nitrobenzene can be converted to the second-order constants k_H by dividing by $[Cu^I]$ and by $[ArBr][Cu^I]$, respectively. The derived values of k_H are also listed in Table II. The scatter as the concentrations of the two reactants is varied is somewhat greater than for the values of k_{Ar_2}, but the correspondence is quite satisfactory in view of the inherent errors in determining the very low concentrations of nitrobenzene and of determining instantaneous rates from the derivatives of equations which have been computer fitted to experimental data.

Mechanism. The first step in the biaryl formation must be a reversible reaction between a solvated cuprous ion, most probably $Cu(NH_3)_2^+$, and a molecule of *o*-bromonitrobenzene to form an intermediate; the latter, or another species in equilibrium with it, must then react with another molecule of aryl bromide to give the product or something which is rapidly converted to product. The alternatives, a trimolecular collision or a reversible association between two aryl bromide molecules followed by an attack of copper(I) on the dimeric complex, appear highly improbable. The reversibility of the first step is demanded by the second-order dependence on aryl bromide concentration.

A free *o*-nitrophenyl radical can be ruled out as an intermediate. This follows from the negligible effect on product distributions of added tetrahydrofuran during the coupling of the aryl halide in view of the very striking increase in the ratio of nitrobenzene to biaryl, observed when the same quantity of THF is present during the formation of *o*-nitrophenyl radicals from the corresponding diazonium ions in the same medium. Evidence against radical intermediates in the heterogeneous Ullmann coupling has previously been obtained by noting the near stereospecificity (retention of configuration) in the coupling of iodomaleate and iodofumarate esters[9] and the lack of 1,5-hydrogen transfer in the coupling of *o*-iodo-*N*,*N*-dimethylbenzamide.[10] If a radical is excluded, it is difficult to formulate the intermediate formed by attack of copper(I) on the aryl bromide as other than an organocopper compound, and it is satisfying that this kinetic evidence for such an intermediate is quite independent of the evidence from trapping experiments[5,9,10,20] obtained previously. Furthermore, such trapping experiments are also successful in the homogeneous Ullmann reaction; addition to the medium of ammonium ion, the strongest acid that can exist in this system, appears to cause a marked diversion of the intermediate to nitrobenzene (Table I).

A two-electron reduction of the organic substrate is involved in the conversion of an aryl halide to an organocopper compound, and this presumably occurs concurrently with a two-electron oxidation of the copper(I).[21] The great similarity between Ullmann couplings and the exchange reaction of aryl and vinyl halides with the anions of copper(I) salts,[3,15] reactions which are believed to proceed by oxidative addition[22] of the carbon-halogen bond to a copper(I),[15] has led to the suggestion that the first step in the Ullmann coupling is also such an oxidative addition,[11] and the results reported here make it difficult to avoid this conclusion, at least in a formal sense. Organocopper(III) intermediates in various reactions have been liberally suggested in recent years;[11,15,17,23-26] many of these[23b,24,25] are considered to form by nucleophilic attacks[27] which are essentially oxidative additions. Nickel(0)[28] and palladium(0),[29] which have similar electronic configurations to copper(I), are also capable of causing the coupling of some aryl halides and oxidative addition has been invoked as the first step. A mechanistic study of the oxidative addition of aryl halides to palladium(0) has revealed that, as in the Ullmann coupling, the rate sequence is ArI > ArBr > ArCl and that electron-withdrawing substituents increase the rate.[30] Furthermore, the oxidative addition of chloroolefins to palladium(0) proceeds with retention of configuration,[31,32] a result which is consistent with an oxidative addition step in the stereospecific Ullmann-type coupling of iodomaleate and iodofumarate esters.[9]

The product of such an oxidative addition is shown as **1** (Scheme I), but it should be realized that the copper almost certainly has other ligands, the nature and number of which are unknown. Perhaps the most surprising result of the present study is that **1** is capable of reacting with aryl bromide without further intervention of copper(I). Since it is difficult to conceive of copper(III) as a nucleophile, it is probably best to regard the carbon-copper bond of **1** as somewhat ionic and the displacement of the bromide (eq 4) to be by nucleophilic attack of a species having *o*-nitrophenyl anion character on the carbon bearing the bromine, possibly with electrophilic assistance to bromide removal by the copper(III). There are at least three possible precedents for nucleophilic behavior of carbon attached to copper(III). Posner and Sterling[33] observed the apparent generation of a cyclopropanone intermediate by reaction of 1,3-dibromo-2-propanone with lithium dimethylcuprate, and Hannah and Smith[26] observed the formation of a cyclopropane from the addition of the same cuprate to the tosyloxy enone **2**. These reactions may be formulated approximately as shown in Scheme II. Perhaps the closest analogies are the reports by Corey of the nucleophilic addition of vinyl carbon atoms bearing halogen to carbonyl groups under the influence of lithium dibutylcuprate.[34]

Scheme I

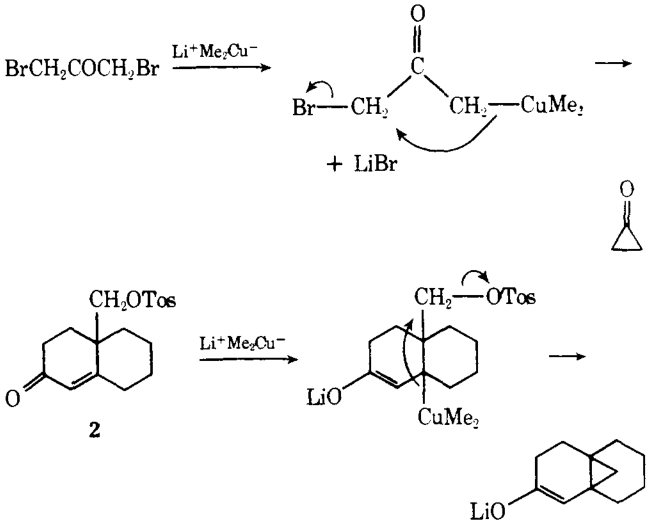
$$\mathrm{ArBr} + \mathrm{Cu^{I}} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \underset{\mathbf{1}}{\mathrm{ArCu^{III}Br}} \qquad (3)$$

$$\mathrm{ArCu^{III}Br} + \mathrm{ArBr} \xrightarrow{k_2} \mathrm{Ar_2} + \mathrm{Cu^{III}Br_2} \qquad (4)$$

$$\mathrm{ArCu^{III}Br} \xrightarrow[\mathrm{H^+}]{k_3} \mathrm{ArH} + \mathrm{Cu^{III}Br} \qquad (5)$$

It is consistent with the behavior of **1** as a nucleophile that it also behaves as a base, being sensitive to protonation by added ammonium ion, in the presence of which nitrobenzene becomes the major product (Table I). Once again, the basicity of **1** is manifested without the intervention of copper(I) since the nitrobenzene formation is first order each in aryl bromide and copper(I). There are also precedents for the protonation of apparent organocopper(III) compounds.[25]

Scheme II



Applying steady-state kinetics to the formation of **1** (Scheme I), eq 6 may be derived for the rate of formation of 2,2′-dinitrobiphenyl.

$$\mathrm{d[Ar_2]/d}t = k_1k_2[\mathrm{ArBr}]^2[\mathrm{Cu^I}]/(k_{-1} + k_3 + k_2[\mathrm{ArBr}]) \qquad (6)$$

Since the order in aryl bromide is accurately two, $(k_{-1} + k_3) \gg k_2[\mathrm{ArBr}]$ and eq 6 becomes

$$\mathrm{d[Ar_2]/d}t = k_1k_2[\mathrm{ArBr}]^2[\mathrm{Cu^I}]/(k_{-1} + k_3) \qquad (7)$$

The experimental third-order rate constant for the production of biaryl (eq 1) is given in eq 8 as a function of the theoretical rate constants of Scheme I.

$$k_{\mathrm{Ar_2}} = k_1k_2/(k_{-1} + k_3) \qquad (8)$$

The same treatment gives eq 9 for the rate of formation of nitrobenzene; since the reaction is first order in [ArBr], $(k_{-1} + k_3) \gg k_2[\mathrm{ArBr}]$ and eq 10 is a good approximation.

$$\mathrm{d[ArH]/d}t = k_1k_3[\mathrm{ArBr}][\mathrm{Cu^I}]/(k_{-1} + k_3 + k_2[\mathrm{ArBr}]) \qquad (9)$$

$$\mathrm{d[ArH]/d}t = k_1k_3[\mathrm{ArBr}][\mathrm{Cu^I}]/(k_{-1} + k_3) \qquad (10)$$

The experimental second-order rate constant for the formation of nitrobenzene (eq 2) is given in eq 11 as a function of the theoretical rate constants of Scheme I.

$$k_{\mathrm{H}} = k_1k_3/(k_{-1} + k_3) \qquad (11)$$

A test of the mechanistic scheme consisted of increasing the acidity of the medium by adding ammonium tetrafluoroborate. This should have the effect of increasing the rate constant k_3 to a value which will be called k_3'. According to eq 11, an increased value of k_3 should lead to an increase in the experimentally determined value of k_{H}, and this expectation is indeed fulfilled (Table II). According to eq 8, another possible consequence of increasing k_3 is to decrease the value of the experimentally determined value of $k_{\mathrm{Ar_2}}$, but this will occur only if k_3' is significant in magnitude compared to k_{-1}; since adding the ammonium salt does not result in a noticeable decrease in $k_{\mathrm{Ar_2}}$, k_3' (and, of course, k_3 as well) must be much smaller than k_{-1}.

Relationship to Heterogeneous Ullmann Coupling. Since the conditions of the homogeneous process investigated here are quite different from those of the usual, heterogeneous Ullmann coupling induced by copper metal, it is not at all certain that the mechanism discussed here is also valid for the heterogeneous process. However, there are a number of striking similarities in the two types of processes. (1) The homogeneous reaction is initiated by copper(I), and there is some indication that copper(I) on the surface of the metal plays a role in the heterogeneous process.[35] (2) Both processes proceed by protonatable intermediates thought to be organocoppers.[1-5,9] (3) Free radicals do not appear as intermediates in either type of reaction.[6,9,10] (4) In both cases, the reactivity sequence is I > Br and ortho nitro groups cause very significant acceleration while ortho carboalkoxy groups are also activating but less so.[1-4,9,11] (5) Diethyl iodofumarate is more reactive than diethyl iodomaleate in both systems.[9,12] The interesting observation that in the conventional Ullmann reaction a good yield of an unsymmetrical biaryl can be obtained from the reaction of an activated and unactivated aryl halide, at a temperature too low for the latter halide alone to react, implies attack on the unactivated aryl halide by an aryl copper, derived from the activated aryl halide, a process which may be similar to the second step of our mechanistic scheme (eq 4). On the other hand, in the Ullman coupling of the unactivated substrate, *p*-iodotoluene in 8-methylquinoline, the biaryl is formed only by self-coupling of an organometallic intermediate.[36] However, this behavior may very well be peculiar to couplings performed in complexing solvents, since the stability of the copper(I) state in such solvents may encourage the reduction by copper metal of the arylcopper(III) to an arylcopper(I); the latter are known to readily undergo a self-coupling reaction.[37] In any event, the two processes are similar enough so that it is reasonable to conclude that they are probably at least mechanistically related; if so, this work provides the first glimpse of some of the intimate mechanistic details of this venerable and useful method of preparing biaryls.

Experimental Section

Coupling of *o*-Bromonitrobenzene. Copper(I) triflate[13] was prepared, undoubtedly as an acetonitrile complex, by heating at reflux for 1 h a magnetically stirred mixture of 1.24 g (2.70 mmol) of $Cu(CF_3SO_3)_2{\cdot}5.5H_2O$ (the light blue salt obtained by drying the freshly prepared hydrate[13] for 1 h in an evacuated desiccator at ambient temperature[11]) and 0.159 g (2.50 mmol) of copper powder (Englehard Magna 1107) in 25 ml of acetone and 1.25 ml of acetonitrile in a closed system under a slight positive pressure of nitrogen. During this time the copper powder disappeared, and the homogeneous solution was a light blue color.

After the solution had cooled to room temperature, *o*-bromonitrobenzene (0.0506 g, 0.250 mmol, Eastman), the gas chromatographic standard, 4,4′-dinitrobiphenyl (0.035 g, 0.125 mmol, Eastman), copper(II) triflate (0.10 g, 0.22 mmol), and 20% aqueous ammonia (5.00 ml) were added, and the mixture was stirred for 24 h under N_2. The contents of the flask were separated into ether and water-soluble portions by a thorough extraction procedure. The dried (magnesium sulfate) ether extract was concentrated, dissolved in acetone, and used for GLC analysis. A further small quantity of *o*-nitrophenol could be recovered from the aqueous phase by acidifying, extracting with ether, washing the extract with water, and analyzing after addition of the same standard. The yields were as follows: 2,2′-dinitrobiphenyl, 89.9%; nitrobenzene, 7.8%; *o*-nitroaniline, 1.2%; *o*-nitrophenol, 0.7%. The same procedure was used for the run in the presence of tetrahydrofuran, except that 1.00 ml of the latter and 24.0 ml of acetone were used instead of 25.0 ml of acetone; in addition to the yields shown in Table I, a 1.6% yield of *o*-nitrophenol was obtained.

Kinetic Study. Copper(I) triflate was prepared as in the preceding experiment. After being cooled, the solution, in an atmosphere of N_2, was placed in a thermostated bath at 30.0 ± 0.1°, and *o*-bromonitrobenzene (see quantities in Table II), copper(II) triflate (0.10 g, 0.22 mmol), and 20% aqueous ammonia (5.00 ml) were added. Samples (4.00 ml) were removed at regular intervals and equilibrated between 10 ml each of water and ether. The ether layer was extracted with water (3 × 10 ml) and the aqueous layer with ether (3 × 5 ml); the latter ether extracts were again extracted with water (2 × 5 ml). The combined organic extract was dried (magnesium sulfate) and concentrated. The residue was dissolved in acetone and, after addition of the standard, 4,4′-dinitrobiphenyl, was used for quantitative analysis of aryl bromide, biaryl, nitrobenzene, *o*-nitrophenol, and *o*-nitroaniline. All rate runs were performed in triplicate and exhibited acceptable reproducibility. Table III gives the experimental data in a typical run employing 5.00 mmol of copper(I) triflate and 0.250 mmol of aryl bromide; the quantities of compounds have been converted to percent reactant remaining or percent yields. In one run, ammonium tetrafluoroborate (0.21 g, 2.0 mmol, Alfa Inorganics) was present in solution during the reaction.

Table III. Data from a Typical Kinetic Run[a,b]

Time, h	% ArBr	% Ar_2	% ArH
0	100.0	0	0
0.25	85.2 ± 0.9	14.4 ± 1.1	0.26 ± 0.01
0.50	72.4 ± 0.8	26.5 ± 0.6	0.48 ± 0.01
1.0	56.8 ± 1.1	42.1 ± 1.2	0.88 ± 0.02
2.0	39.2 ± 0.9	59.4 ± 0.8	1.38 ± 0.05
4.0	23.6 ± 0.8	74.0 ± 0.9	2.14 ± 0.06
6.0	17.6 ± 0.7	79.3 ± 1.2	2.64 ± 0.10
8.0	14.0 ± 1.2	81.8 ± 0.7	3.08 ± 0.20

[a] The quantities of copper(I) triflate and aryl bromide were 5.00 and 0.250 mmol, respectively. See Experimental Section for conditions. [b] Average deviations for triplicate runs are given.

Decomposition of *o*-Nitrobenzenediazonium Tetrafluoroborate. The diazonium salt was prepared by treatment of a concentrated solution of *o*-nitroaniline in aqueous tetrafluoroboric acid with sodium nitrite.[38] After being dried in a vacuum desiccator, the yellow solid had mp 110° dec. Its infrared spectrum (Nujol) exhibited a strong diazonium absorption at 2298 cm^{-1} and no absorption in the OH or NH region. Copper(I) triflate was prepared as described above; in one experiment, 25.0 ml of acetone was used as above, and in the other 24.0 ml of acetone was used, and 1.00 ml of THF was added after the redox reaction was complete. To the cooled solution was added 20% aqueous ammonia (5.00 ml), copper(II) triflate (0.10 g, 0.22 mmol), the GLC standard, 4,4′-dinitrobiphenyl (0.035 g, 0.125 mmol), and, in small portions, the diazonium salt (0.059 g, 0.250 mmol). The mixture was stirred under a nitrogen atmosphere for 20 min and then worked up as in the coupling experiment described at the beginning of this section. Yields for the runs with and without THF are given in Table I.

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Polar and Stereochemical Factors in the Carbalumination of Olefins. Addition of Triphenylaluminum to 6-Substituted Benzonorbornadienes[1]

John J. Eisch* and Nicholas E. Burlinson

Contribution from the Departments of Chemistry at the Catholic University of America, Washington, D.C. 20017, and the State University of New York at Binghamton, Binghamton, New York 13901.

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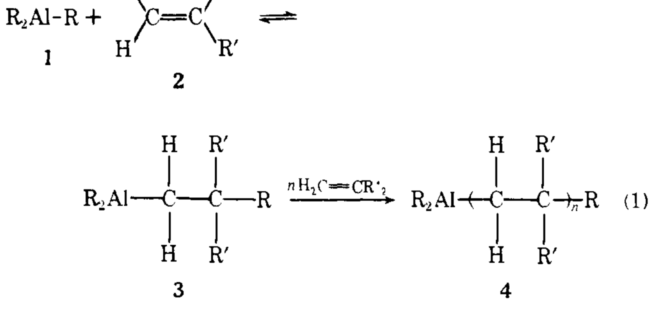
Abstract: The electronic and stereochemical factors in the carbalumination of olefins were assessed by a study of the addition of triphenylaluminum to 6-substituted benzonorbornadienes bearing protio, chloro, methyl, and fluoro groups. On the basis of the deuterium-containing 2-phenylbenzonorbornene obtained by treatment of the aluminum adduct with D_2O and the 3-phenylbenzonorbornen-2-one obtained by oxidative work-up, the carbalumination was shown to occur in an exo,syn manner without skeletal rearrangements. The regioisomeric ratios of adducts were determined to be 53:47 (7Me:6Me) for the 6-methyl case and 30:70 (7F:6F) for the 6-fluoro case by the following procedure: (a) air oxidation of the carbalumination adducts; (b) Jones oxidation of the resulting mixture of ketones and alcohol to exclusively the isomeric ketones; and (c) ^1H or ^{19}F NMR analysis of these ketones, using $Eu(fod)_3$ to separate the resonance signals and to make structural assignments. The relative reactivities of the four benzonorbornadienes in carbalumination, as determined at $80.0 \pm 0.2°$ in benzene by the homocompetitive method, were 0.66 (Cl), 0.80 (F), 1.00 (H), and 1.30 (CH_3). The stereochemistry and substituent effects point to electrophilic attack by monomeric $(C_6H_5)_3Al$ on the olefin in the rate-determining step. Both the relative rates and the limited data on regioisomeric ratios correlate better with the modified parameter, $(\sigma_p + \sigma_m)/2$, than with σ_p^+ or σ_p. The transition state of the rate-determining step is considered to resemble a π complex, while the regioisomeric products are thought to arise in a relatively fast step whose transition state resembles a σ complex. Such a mechanism seems in best accord with the differing influences of substituents on overall rate and on product distribution.

The addition of the aluminum–carbon bond to unconjugated olefinic substrates, first reported by Ziegler and his coworkers in 1950,[2] is a reaction of great significance for organic synthesis (eq 1). First of all, the initial adduct **3**, which results from such carbalumination of **2** by **1**, is itself an aluminum alkyl and can, in principle, react with additional olefinic units to produce a long-chain aluminum alkyl **4**. With olefins like ethylene (**2**, R′ = H), the resulting straight-chain aluminum alkyls (**4**, R′ = H; R = C_2H_5) can readily be transformed into higher molecular weight α ole-



$$R_2Al\text{-}R + H_2C{=}CR'_2 \rightleftharpoons R_2Al{-}CH_2{-}CR'_2{-}R \xrightarrow{n\,H_2C{=}CR'_2} R_2Al{-}(CH_2{-}CR'_2)_n{-}R \quad (1)$$

1 **2** **3** **4**

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* Author to whom correspondence should be addressed at the State University of New York at Binghamton.