products (containing some benzyl halide) were analyzed as before.

Registry No.—$RC_6H_4CH_2S(CH_3)_2X$: R = p-CH_3O, X = Cl, 14181-51-2; R = p-CH_3O, X = Br, 14181-52-3; R = p-CH_3O, X = I, 14181-53-4; R = p-CH_3O, X = CH_3SO_3, 14264-68-7; R = p-CH_3, X = Cl, 14182-11-7; R = p-CH_3, X = Br, 14182-12-8; R = p-CH_3, X = I, 14182-13-9; R = H, X = Cl, 14182-14-0; R = H, X = Br, 14182-15-1; R = H, X = I, 14182-82-2; R = H, X = CH_3SO_3, 14182-17-3; R = p-Cl, X = Cl, 14182-18-4; R = p-Cl, X = Br, 14182-19-5; R = p-Cl, X = I, 14182-20-8; R = m-NO_2, X = Cl, 14182-21-9; R = m-NO_2, X = Br, 14182-22-0; R = m-NO_2, X = I, 14182-23-1; R = m-NO_2, X = CH_3SO_3, 14182-24-2; R = p-NO_2, X = Cl, 14182-25-3; R = p-NO_2, X = Br, 14182-26-4; R = p-NO_2, X = I, 14182-27-5; R = p-NO_2, X = CH_3SO_3, 14182-28-6.

The Mechanism of the Copper-Induced Pschorr Cyclization. A New Phenol Synthesis Involving Hydroxylation of the Intermediate Radical by Cupric Ion[1]

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The copper-catalyzed decomposition of aryl diazonium salts at low temperatures has been shown to yield an aryl radical and has been utilized to effect essentially unidirectional (a) Pschorr cyclizations, (b) hydroxylations, and (c) reductions. Excellent yields of the following products are obtained when the cuprous oxide catalyzed decompositions of 2-diazobenzophenone tetrafluoroborate are carried out under the conditions specified: (a) fluorenone, in dilute aqueous acid; (b) 2-hydroxybenzophenone, in dilute acid in the presence of a large excess of aquated cupric ion; and (c) benzophenone, in dioxane. Analogous results are obtained in decompositions of 2-(o-diazobenzoyl)naphthalene tetrafluoroborate; α-ring closure to give benzo[c]fluorenone exceeds β-ring closure to give benzo[b]fluorenone in a 9:1 ratio at low temperatures. These results are discussed in terms of the mechanism of the copper-catalyzed reaction which, contrary to suggestions in the literature, does not involve a cationic component. The oxidation by cupric ions of aryl radicals generated by diazonium ion decomposition constitutes a promising new method for the introduction of hydroxyl groups into aromatic nuclei. This method leads to high yields of phenols and no "diazo resins" which accompany the thermal production of phenols from diazonium salts. Phenols which could not be previously prepared from the corresponding amines are accessible by this new procedure. Evidence is presented that this reaction does not involve a phenyl cation intermediate but instead proceeds by transfer of $H_2O^{+\cdot}$ from the hydration shell of the cupric ion to the aryl radical (ligand radical transfer).

Among reactions of aromatic diazonium salts,[2] Pschorr cyclizations[3,4] (for example, **1** → **5** and **8** → **9** + **10**) are perhaps the most enigmatic. They are plagued with side reactions such as reduction which produces arenes, reductive coupling which yields symmetrical biaryls and azoarenes, halogenation, and phenol formation.[2,3] Furthermore, a survey of the very considerable literature on the subject helps very little in allowing a prediction as to the best reaction conditions for a given case. In fact, Pschorr cyclizations have been attempted under a wide variety of conditions: the diazonium salt is sometimes suspended in the medium, but more often it is in a solution which is usually acidic (basic solutions have also been used); the reaction is conducted in the presence or absence of catalysts, usually copper metal, but sometimes other copper compounds are used; the temperature is usually 50° or higher but there are many examples of decomposition at room temperature. In very few, if any, cases have the reaction conditions been chosen on a rational basis; frequently analogies are used but one can almost always find other analogies suggesting different conditions. At present, one of the major dilemmas is whether or not a copper catalyst should be used. In his review, Leake concludes, "In spite of its recorded effectiveness, the usefulness of copper cannot be predicted."[4]

Advances during the last decade in our understanding of the mechanisms of diazonium decomposition, especially with regard to the catalyzed reaction, have now provided the basis for a reevaluation of these problems. It has long been suspected that thermal decomposition of diazonium salts in acidic solution produces phenyl cations and this now appears to be well established, especially when the anion is not a good reducing agent (*e.g.*, fluoroborate and similar ions are the best choices, whereas chloride could cause a radical reaction).[2,3,5–7] On the other hand, decompositions in alkaline solution[8] are radical in character as are those in acid solution which are catalyzed by copper metal or cuprous compounds.[5,7,8b,9–13]

Since intramolecular arylations can be executed in either a radical or an electrophilic fashion, the choice of a radical or cationic decomposition rests with an

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[1] (a) This investigation was supported by Grant GP3821 from the National Science Foundation. (b) Presented in part at the 151st National Meeting of the American Chemical Society, Pittsburgh, Pa., March 1966, Abstract K 103.

[2] H. Zollinger, "Diazo and Azo Chemistry," Interscience Publishers, Inc., New York, N. Y., 1961, and references therein.

[3] D. F. DeTar, *Org. Reactions*, **9**, 409 (1957).

[4] P. H. Leake, *Chem. Rev.*, **56**, 27 (1956).

[5] A. N. Nesmeyanov, L. G. Makarova, and T. P. Tolstaya, *Tetrahedron*, **1**, 145 (1957); G. A. Olah and W. S. Tolgyesi, *J. Org. Chem.*, **26**, 2053 (1961).

[6] (a) T. Cohen and J. Lipowitz, *J. Am. Chem. Soc.*, **86**, 2514 (1964); (b) T. Cohen, A. H. Dinwoodie, and L. D. McKeever, *J. Org. Chem.*, **27**, 3385 (1962).

[7] A. H. Lewin, A. H. Dinwoodie, and T. Cohen, *Tetrahedron*, **22**, 1527 (1966).

[8] (a) C. Rüchardt and E. Merz, *Tetrahedron Letters*, 2431 (1964); (b) G. H. Williams, "Homolytic Aromatic Substitution," Pergamon Press Inc., New York, N. Y., 1960, p 28.

[9] W. A. Waters, "The Chemistry of Free Radicals," The Clarendon Press, Oxford, 1946, p 165; D. H. Hey and T. M. Moynehan, *J. Chem. Soc.*, 1563 (1959); L. G. Makarova and M. K. Matveeva, *Izv. Akad. Nauk SSSR, Otd. Khim. Nauk*, 1974 (1960).

[10] R. Huisgen and W. D. Zahler, *Chem. Ber.*, **96**, 736 (1963).

[11] J. K. Kochi, *J. Am. Chem. Soc.*, **79**, 2942 (1957).

[12] D. C. Nonhebel and W. A. Waters, *Proc. Roy. Soc.*, **A242**, 16 (1957).

[13] S. C. Dickerman, K. Weiss, and A. K. Ingberman, *J. Org. Chem.*, **21**, 380 (1956); C. S. Rondestvedt, Jr., *Org. Reactions*, **11**, 189 (1960).

evaluation of the potential competing processes. Generally, the most serious side reaction in the radical decomposition is hydrogen atom abstraction, either from an intramolecular donor or from the solvent.[7] Other side reactions include chlorine abstraction from the solvent, abstraction of a ligand radical from a Cu(II) salt,[7,11–14] and reaction of the radical with a cuprous species to form an organocopper intermediate[15a] which can undergo protolysis to an arene, self-coupling to form a biaryl or addition to unreacted diazonium ion to form an azoarene.[15] In the thermal decomposition in acidic solution the most serious competing process is the reaction of the aryl cation with a nucleophilic solvent.[3,6b,7,16] Others include reaction with the counterion,[17] intramolecular hydride ion abstraction,[6,7] and the reaction of the diazonium ion with various nucleophiles, such as phenols or neighboring double bonds.[3]

In any given ring closure, it should usually be possible, by careful control of the reaction conditions, to avoid largely one or the other set of side reactions and then the choice of cationic or radical conditions becomes obvious. It is, of course, very clear that the Pschorr reaction should not be carried out under conditions that favor both radical and cationic intermediates since the number of competing side reactions will then be unnecessarily high. Therefore, of the two most common methods[3] of performing this reaction, heating in acid solution with and without a copper catalyst, the former is unacceptable. *In the catalyzed reaction at elevated temperatures, there is a distinct danger that both mechanisms will occur and we believe that this is mainly responsible for the extensive formation of by-products in Pschorr cyclizations and for the considerable confusion concerning the mechanisms.* The high temperatures are presumably used because copper metal promoted diazonium decompositions are often very slow at or below room temperature. However, an obvious method of increasing the reaction rate at a low temperature is to use large quantities of copper. Alternatively and more satisfactorily, one may employ catalysis by cuprous oxide, which has been shown to produce radicals very effectively from diazonium ions at low temperatures.[7]

In this paper, we demonstrate the application of these principles to two systems which are among the few for which reliable data are available from fairly systematic previous studies. The first of these, 2-diazobenzophenone **1**, was shown by DeTar and Relyea[18] to produce fluorenone (**5**) and *o*-hydroxybenzophenone (**4**, Z = OH) both in the absence and presence of copper metal. The second system, 2-(*o*-diazobenzoyl)naphthalene (**8**) was originally recognized by Huisgen and Zahler[10] as a particularly informative one because in addition to the usual product ratios, the ratio of α to β ring closure might reveal information about the mode of ring closure. In our study of the latter system, we deal with the assertion made by Huisgen and Zahler[10] that in the copper-promoted reaction, part of the product is derived from aryl radicals and part from aryl cations, the latter being produced by oxidation (electron transfer) of the aryl radicals by copper salts. If true, of course, this radical oxidation could seriously limit the applicability of the above analysis.[19,20]

Results and Discussion

2-Aminobenzophenone.—Whereas only very few phenanthrene syntheses can be carried out successfully in the absence of copper,[2] most preparations of dibenzofurans and fluorenones do not require the use of metal catalysts.[2] It has been pointed out, however, that even in the fluorenone synthesis the yields of cyclized product were higher when copper powder was present.[18] The careful work of DeTar and Relyea[18] has established that the thermal decomposition of the 2-diazobenzophenone (**1**) salt proceeds by heterolysis of the C–N bond to produce a phenyl cation which can ring close and then lose a proton to give fluorenone but it can also undergo competing nucleophilic reactions leading to substitution products. In their hands, this competition led to 65% of fluorenone and 35% of 2-hydroxybenzophenone and this ratio was unchanged in the presence of cupric sulfate.

Under the same conditions, the copper metal induced decomposition was found to produce 71% ketone and 21% phenol. In Scheme I we have applied the above mechanistic principles to the catalyzed decomposition of *o*-diazobenzophenone (**1**) by showing all of the reasonable reaction paths of the radical **2** resulting from the one-electron reduction of **1** by copper metal or cuprous oxide which is undoubtedly present on the metal surface. This radical can cyclize to the more stable radical **3** which, by oxidation (probably by Cu(II), but conceivably to some extent by traces of oxygen in the system), followed by loss of a proton, could be converted to fluorenone (**5**).[21] Alternatively, the radical **2** could abstract a ligand radical from the coordination shell of a Cu(II) ion to yield substitution poduct **4**. In the presence of hydrogen atom donors, **2** would be expected to be converted to benzophenone (**6**), while in the presence of cuprous ions there might result an organometallic compound such as **7**, which in protic solvents should yield benzophenone.[22]

Thus, in the absence of external hydrogen atom donors, efficient ligand radical-transfer agents, and high concentrations of Cu(I),[23,24] a good yield of fluorenone is to be expected.

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[14] J. K. Kochi, *Tetrahedron*, **18**, 483 (1962); J. K. Kochi and R. V. Subramanian, *J. Am. Chem. Soc.*, **87**, 1508 (1965); H. Asscher and D. Vofsi, *J. Chem. Soc.*, 3921 (1963).

[15] (a) T. Cohen and A. H. Lewin, *J. Am. Chem. Soc.*, **88**, 4521 (1966); (b) A. H. Lewin and T. Cohen, *Tetrahedron Letters*, 4531 (1965).

[16] T. Cohen and J. Lipowitz, *ibid.*, 3721 (1964).

[17] This reaction is favored in nonpolar solvents in which ion pairing is important.[16]

[18] D. F. DeTar and D. I. Relyea, *J. Am. Chem. Soc.*, **76**, 1680 (1954).

[19] The converse hypothesis, that the catalyzed reaction produces aryl cations which are subsequently reduced to aryl radicals, has also been proposed,[20] but the results on which this suggestion is based can more reasonably be explained by Scheme I; that is, that cuprous ions are effective promoters of a radical decomposition of the diazonium ion, while the cationic reaction is a result of the competing thermal decomposition.

[20] J. L. Huppatz and W. H. F. Sasse, *Australian J. Chem.*, **16**, 417 (1963).

[21] A ligand radical transfer followed by loss of HZ cannot be ruled out for the conversion of **3** to **5**.

[22] The structure **7** is used as an example only. The exact nature of the organometallic intermediate is not known.[15a]

[23] Very little is yet known about the suppression of organocopper formation in these reactions. However, a perusal of the literature[2,24] indicates that the yields of products derivable from arylcopper appear to increase in nonaqueous solvents and in the presence of complexing agents such as ammonia or chloride ion. Since cuprous ions as such are unstable in water solution devoid of complexing agents, this is not unexpected.

[24] R. G. R. Bacon and H. A. O. Hill, *Quart. Rev. (London)*, **19**, 95 (1965); W. A. Cowdrey and D. S. Davies, *ibid.*, **6**, 358 (1952); E. Pfeil, *Angew. Chem.*, **65**, 155 (1953).

TABLE I

DECOMPOSITION PRODUCTS OF 2-DIAZOBENZOPHENONE TETRAFLUOROBORATE IN 0.10 *N* SULFURIC ACID

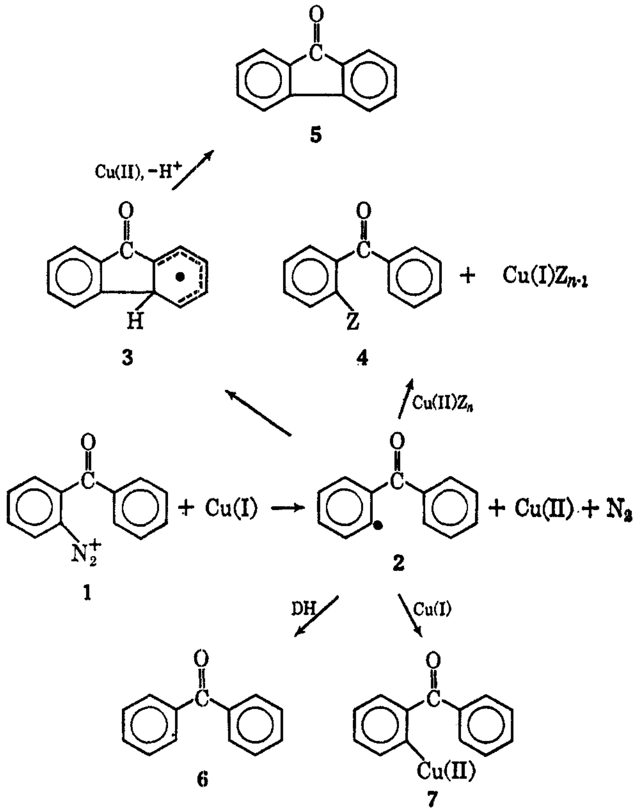
Run	Temp, °C	Catalyst	Additive	Product yields, %[a],[b] Benzophenone 6	2-Hydroxybenzophenone 4, Z = OH	Fluorenone 5
1	45				32	68
2	45	Cu[c]			33	67
3	45	Cu_2O[d]		6	1	93
4	25	Cu[e]		6	3	91
5	25	Cu_2O[d]		3	4	93
6	25	Cu[e,f]		9	6	85
7	25	Cu[g]	$Cu(NO_3)_2$[h]	6	18	76
8	25	Cu_2O[d]	$Cu(NO_3)_2$[h]	7	18	75
9	25	Cu[g]	$Cu(NO_3)_2$[i]	2	87	11
10	25	Cu_2O[d]	$Cu(NO_3)_2$[i]	1	88	11
11	25	Cu_2O[d]	$Cu(NO_3)_2$,[h] $NaNO_3$[i]	14	17	69
12	25	Cu_2O[d]	Dioxane[j]	100		

[a] Determined by vpc. [b] Normalized to 100%; total recovery was 86–97%. [c] 1.6 g-atoms/mole of reactant. [d] 1.7 equiv/mole of reactant. [e] 48 g-atoms/mole of reactant. [f] Gattermann copper. [g] 96 g-atoms/mole of reactant. [h] 3.5 moles/mole of reactant. [i] 350 moles/mole of reactant. [j] Without acid.

Evidence in support of Scheme I has been sought by comparing the composition of the product mixtures under a variety of conditions. The results are summarized in Table I. The product composition of the thermal reaction of the tetrafluoroborate salt of 1 in dilute acid (run 1) is in fair agreement with the results reported by DeTar.[18] The addition of a small amount of copper (run 2) has no effect on either the product composition or apparent reaction rate, indicating that the copper reaction under these conditions is incapable of competing with the thermal decomposition. On the other hand, addition of a small amount of cuprous oxide as catalyst (run 3) has a striking effect on both the product composition and the reaction rate. The cuprous oxide catalyzed reaction occurs essentially instantaneously and yields very predominantly the ring-closed product fluorenene (**5**). It is clear both from previous work[7] and from this investigation (runs 4–6) that catalysis by copper (either commercial or freshly precipitated Gattermann) and cuprous oxide leads to one and the same reaction,[25] cuprous oxide being, however, a greatly superior catalyst,[26] successfully eliminating any of the competing thermal reactions (which yield phenol) even at the higher temperature. Thus, in terms of Scheme I, it is seen that in the absence of an external hydrogen atom source (water is a notoriously poor one) and of ligand radical-transfer agents[27] the reaction proceeds mainly through the σ complex **3**. When the concentration of ligand radical-transfer agent in solution is increased by adding cupric ions (in the form of cupric nitrate) to the reaction (runs 7–10), the yields of the phenol **4** (Z = OH) increase proportionately, in good agreement with Scheme I. Again, the reactions catalyzed by cuprous oxide lead to the same product mixtures as the copper-catalyzed ones. It could be argued that the role of the excess cupric ion in solution is not as the ligand radical-transfer agent but as the oxidizing agent by means of an electron transfer. This oxidation pathway appears highly unlikely, *a priori*, because of the high energy associated with the phenyl cation; it also seems to be ruled out to a large extent by the results of runs 9 and 10 since, quite contrary to the results of these runs, the cation resulting from oxidation of the radical **2** would be expected to yield twice as much fluorenone (**5**) as 2-hydroxybenzophenone (**4**, Z = OH) based on the results obtained in the thermal decomposition.

SCHEME I

SUGGESTED REACTION COURSE OF THE COPPER-CATALYZED DECOMPOSITION OF 2-DIAZOBENZOPHENONE TETRAFLUOROBORATE



Experiments were next undertaken to determine which of the three conceivable ligand radicals, $NO_3\cdot$, $HO\cdot$, or $H_2O\cdot^+$, was actually being transferred from the coordination shell of the cupric ion to the phenyl radical **2**. The first of these was eliminated as a possibility

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(25) It should be noted that in all cases tested to date in these laboratories the products of the copper-catalyzed reaction are the same as those of the cuprous oxide catalyzed one with the latter catalyst greatly enhancing the reaction rate.

(26) Whereas the thermal reaction requires 17 hr to be completed at 45°, the cuprous oxide catalyzed reaction is over in *ca.* 5 min.

(27) The concentration of cupric species in the solution is undoubtedly quite low.

when it was shown that the decomposition of the fluoroborate salt of **1** in a solution containing a small quantity of cupric nitrate and a large excess of sodium nitrate (run 11) furnishes the same yield of phenol as similar decompositions performed in the absence of added sodium nitrate (runs 7 and 8).

A choice between the transfer of HO· and $H_2O\cdot^+$ can be made by determining whether the efficiency of oxygen transfer is affected by the acidity of the medium.[28] Since the acidity constant[29] of the cupric ion (the equilibrium constant of the reaction shown below) is *ca.* $10^{-7.5}$ at 25°, the concentration of a hydrated cupric ion should be insensitive to pH in acidic solutions while that of $CuOH^+$, which is present only in minute amounts, should be inversely proportional to the hydrogen ion concentration (eq 1). Assuming that the

$$Cu^{2+}(aq) \rightleftharpoons CuOH^+(aq) + H^+(aq) \qquad (1)$$

rate constant for transfer of HO· is greater than that for transfer of $H_2O\cdot^+$,[28] and that a change in pH would not affect the rate of ring closure of the radical **2**, one would expect an increase in acidity to cause a decrease in the ratio of phenol to fluorenone produced if the concentration of $CuOH^+$ is significantly involved in the rate law of the oxygen transfer. On the other hand, if the hydrated cupric ion is the oxidant, the ratio of phenol to fluorenone should remain constant when the acidity is changed. Experimentally, it is indeed found that this ratio varies only between 4.3 and 4.6 when the acidity is changed 100-fold (Table II). It can thus be concluded that $H_2O\cdot^+$ rather than HO· is probably being transferred in these oxidations.

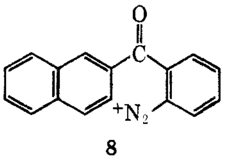
TABLE II

THE EFFECT OF ACIDITY ON THE RATIO OF PHENOL TO FLUORENONE

Acid concentration, *N*	Products, % Benzophenone **6**	 2-Hydroxybenzophenone **4**, Z = OH	 Fluorenone **5**	Ratio **4/5**
1.0	1.8	80.1	18.1	4.4
0.10	1.3	81.3	17.4	4.6
0.010	18.5	66.1	15.4	4.3

In the presence of the external hydrogen atom source (DH) dioxane (run 12), the reaction, which yields quite cleanly benzophenone (**6**), presumably proceeds exclusively by way of hydrogen atom abstraction by radical **2** from the solvent. Since water is an exceptionally ineffective hydrogen atom donor, the genesis of the small quantity of benzophenone produced in the catalyzed decompositions in water is unclear. One possibility is that the radical **2** removes a hydrogen atom from the phenolic OH group of 2-hydroxybenzophenone (**4**, Z = OH). Another is the hydrolysis of an organocopper intermediate such as **7** or its reduction product ArCu(I). However, both of these routes are unacceptable since it was shown that benzophenone produced in heavy water is devoid of deuterium. The abstraction of a hydrogen atom by **2** from the σ complex **3** would appear to be an unlikely process requiring the collision of two transient intermediates in a dilute solution. Furthermore, such a mechanism requires a decrease in the yield of benzophenone when the cupric concentration is increased (thereby increasing the rate of the competing conversion **3** → **5**) and this is inconsistent with the data (compare runs 5 and 8).

2-(*o*-Aminobenzoyl)naphthalene.—Decomposition of the diazonium salt (**8**) and the nitrosoacylamine derived from 2-(*o*-aminobenzoyl)naphthalene under a variety of conditions was investigated by Huisgen and Zahler,[10] particular emphasis being placed on the ratio of α- to β-ring closure, yielding angular and linear benzofluorenones **9** and **10**, respectively. It was suggested



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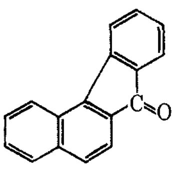
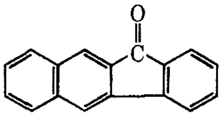


9



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by the authors that this ratio (**9**:**10**) provides a useful criterion for differentiation between ionic and radical cyclization. The ratio of benzofluorenones is relatively low (2.4) in the products of the thermal decomposition in acid medium, a reaction which proceeds *via* a cationic intermediate, and quite high (9.5) in the products of the basic decomposition of the diazonium salt and of the decomposition of the nitrosoacylamine, both of which proceed *via* a radical intermediate. Since the copper-catalyzed decomposition led to an intermediate value for the ratio of **9** to **10** (4.4), they proposed that the phenyl radical formed by homolytic decomposition is partially oxidized in solution to the corresponding phenyl cation by cuprous ions which are produced from metallic copper during the decomposition. The phenyl radical then ring closes in a ratio of 9.5:1 of angular to linear benzofluorenone and the phenyl cation ring closes in a ratio of 2.4:1, leading to the intermediate value of 4.4:1.

In view of the investigation described above, this latter explanation appears unlikely since oxidation of a phenyl radical to a cation by means of electron transfer does not take place even in the presence of a large excess of cupric ions, which are much more effective oxidizing agents than cuprous ions.

The results of our decompositions of the diazonium tetrafluoroborate of 2-(*o*-aminobenzoyl)naphthalene are shown in Table III. The results of the thermal decomposition of the 2-(*o*-diazobenzoyl)naphthalene tetrafluoroborate suspended in acid (runs 13 and 17) are in good agreement with the results reported by Huisgen[10] with α-ring closure being *ca.* 2.4 times more rapid than β as indicated by the ratio of **9**:**10**. This ratio is apparently typical of the ionic ring closure in this system, as suggested by Huisgen.[10] It should be noted that the phenol is produced, as expected, in these runs. The decompositions catalyzed by copper powder or cuprous oxide at low temperature (runs 16 and 18–21) all lead to a much higher ratio of **9**:**10**, averaging about 9, in accordance with expectations based on Huisgen's[10] low-temperature decompositions. The results all parallel those obtained for the 2-diazobenzophenone system and further support Scheme I. Briefly it can be seen that these radical reactions lead to phenol only upon the addition of a large amount of ligand radical-transfer

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[28] R. K. Murmann, H. Taube, and F. A. Posey, *J. Am. Chem. Soc.*, **79**, 262 (1957), and papers cited therein.

[29] "Stability Constants," Special Publication No. 17, A. Martell and L. G. Sillén, Ed., The Chemical Society, 1964, p 59.

TABLE III

DECOMPOSITION PRODUCTS OF 2-(*o*-DIAZOBENZOYL)NAPHTHALENE TETRAFLUOROBORATE

Run	Temp, °C	Medium[c]	Catalyst	Additive	Product yields, %[a,b] 2-Benzoyl-naphthalene	2-(*o*-Hydroxy-benzoyl)-naphthalene	Benzo[*c*]-fluorenone **9**	Benzo[*b*]-fluorenone **10**	Ratio of **9:10**
13	100	4.0 *N* H_2SO_4				33	47	20	2.4
14	100	4.0 *N* H_2SO_4	Cu[d]		2.4	0.8	80.9	15.9	5.1
15	65	4.0 *N* H_2SO_4	Cu[d]		2.8	Trace	84.0	13.2	6.4
16	25	4.0 *N* H_2SO_4	Cu[e]		5.4		83.9	10.7	7.8
17	25	0.10 *N* H_2SO_4				42.4	40.1	17.5	2.3
18	25	0.10 *N* H_2SO_4	Cu[d]		18.1		74.0	7.9	9.5
19	25	0.10 *N* H_2SO_4	Cu_2O[f]		31.8		61.2	7.0	8.9
20	25	0.10 *N* H_2SO_4	Cu_2O[f]	$Cu(NO_3)_2$[g]	16.5	27.2	50.5	5.8	8.7
21	25	Dioxane	Cu_2O[f]		75.0		22.5	2.5	9.0

[a] Determined by vpc. [b] Normalized to 100%; total recovery was 76–94%. [c] Suspension. [d] 800 g-atoms/mole of reactant. [e] 4000 g-atoms/mole of reactant. [f] 1.1 moles/mole of reactant. [g] 500 moles/mole of reactant.

agent (cupric species, run 20) which causes the ligand radical-transfer reaction pathway to become competitive. In the presence of an external hydrogen atom donor (dioxane, run 21) the reaction is largely diverted to produce the reduced product, 2-benzoylnaphthalene. However, in spite of all these changes the α to β ratio of benzofluorenones remains essentially constant and high (*ca.* 9). Of particular interest is the decomposition with added cupric nitrate (run 20) since it shows the lack of effect of an oxidizing agent on the benzofluorenone ratio. This high ratio of **9**:**10** = 9 appears to be typical of the radical cyclization at low temperature. The difference between the ratio obtained in the thermal decomposition (2.3–2.4) and in the copper-catalyzed reaction (9) is a reflection of the high reactivity and low selectivity of the phenyl cation *vs.* the greater selectivity of the more stable phenyl radical.

The results of the copper-catalyzed decomposition seem to be temperature dependent (runs 14–16) with the benzofluorenone ratio decreasing at higher temperatures, whereas this ratio is essentially temperature invariant in the thermal reaction. A consideration of the intermediates involved in the radical reaction shows the one leading to the angular benzophenone **9** to be of lower energy and this is borne out by the results of the low-temperature decompositions. As the temperature is increased the energy difference between the transition states leading to angular and linear benzofluorenone becomes less important and as usual over-all selectivity is decreased, resulting in a lower ratio of benzofluorenone **9**:**10**. *It is clear that this lowered ratio is not due to reaction through an intermediate phenyl cation (produced by competing thermal reaction or by oxidation of a phenyl radical) since no phenol is obtained in these decompositions.* It should be noted that the benzofluorenone ratio of 4.4 reported by Huisgen[10] in the base-catalyzed decomposition at 100° can also be explained on this basis.

It appears from our results (runs 16 and 18) that the ratio of **9**:**10** might also be somewhat dependent on the concentration of the acid used as the reaction medium. We have, however, not investigated this further.

The high yield of reduction product, 2-benzoylnaphthalene, obtained in some of the catalyzed decompositions is surprising and unexplained. As in the *o*-diazobenzophenone case, a decomposition was carried out in heavy water (under the conditions of run 19) and no deuterium was found in any of the products. There appears to be a correlation between acidity of the medium and the extent of reduction, the more reduction occurring in the less acidic solutions. However, the nature of the reducing agent remains obscure.

Conclusions

These results support the suggestion that the Pschorr cyclization can take place by more than one mechanism[3] and substantiate the reaction pathway proposed for the thermal and copper-catalyzed decompositions of aryl diazonium salts.[7] Moreover, they provide an approach to actually controlling the course and products of such decompositions. Whereas there are rare cases in which the thermal decomposition will effect Pschorr ring closure more successfully than the radical reaction,[30] in general, because nucleophilic attack on the aryl cation is avioded and the greater selectivity of aryl radicals is brought into play, the copper-promoted reaction should be a better choice to effect either ring closure, reduction, or hydroxylation (see below) provided that suitable reaction conditions are chosen as recommended below. (a) Cuprous oxide or a large excess of metallic copper should be used to ensure efficient homolytic cleavage. (b) The reaction temperature should be kept low to avoid competition from thermal decomposition. (c) Dilute sulfuric acid is a suitable solvent (even if the reaction has to be carried out as a suspension). (d) To effect reduction a hydrogen atom donor such as dioxane should be used as solvent. This method appears to be at least as effective as the hypophosphorous acid procedure which is usually employed. (e) To effect substitution a large excess of both the ligand radical-transfer agent (cupric species) and the corresponding ligand should be present;[31,32] solvents used for (d) should be avoided.

The probable reasons for the many failures of attempted Pschorr cyclizations reported in the literature become evident in light of the above discussion. Probably the most common procedural error is to carry out the copper-induced reaction at elevated temperatures thus allowing thermal decomposition to compete.

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(30) One example is the diazonium ion derived from *o*-amino-N,N-dibenzylbenzamide which produces a 15% yield of the seven-membered ring Pschorr product under thermal conditions,[6b] but which gives none in the copper-catalyzed reaction because of the very effective competition from an intramolecular hydrogen atom transfer.[7]

(31) An excess of ligands is necessary since the higher complexes of copper(II) are more effective in ligand radical transfer than the lower complexes.[32]

(32) M. Asscher and D. Vofsi, *J. Chem. Soc.*, 4962 (1964); J. K. Kochi, *J. Am. Chem. Soc.*, **79**, 2942 (1957); see ref 5.

Another has been the use of solvents which are potential hydrogen atom donors such as acetone.

Hydroxylation by means of ligand radical transfer is of particular interest and importance as a new method for the preparation of phenols. We have prepared *p*-bromophenol from *p*-bromobenzenediazonium tetrafluoroborate in 87% yield utilizing ligand radical transfer; the same salt yielded 53% phenol when decomposed thermally in acid solution and this was accompanied by "diazo resins." This new approach also leads to high yields of phenol in cases where ring closure is a competing reaction, as exemplified by the results obtained in the decomposition of the 2-diazobenzophenone salt. There is no other obvious method of converting the corresponding amine to the phenol. There are many other cases where phenol formation by means of diazonium ion decomposition has heretofore been impossible. One example is the formation of 6-nitroindazole rather than a phenol in the thermal decomposition of the diazonium salt of 2-methyl-5-nitroaniline.[33] Thus, it might not only be possible to improve the yields of phenols in aryl diazonium ion decomposition reactions by utilizing the ligand radical transfer of water, but this method may provide a new approach to phenols which were previously inaccessible from the corresponding amines.

Experimental Section

2-Diazobenzophenone Tetrafluoroborate.—Diazotization of 2-aminobenzophenone (K & K Chemical Co.) by the usual procedure[34] gave an 80% yield of fine, pale yellow needles, which could be kept in the freezer without discoloration for about 1 month. Infrared bands (Nujol) appeared at 2263 (N_2^+), 1640 (s, CO), and 1040 cm^{-1} (broad, BF).

2-(*o*-Diazobenzoyl)naphthalene Tetrafluoroborate.—The usual diazotization procedure[34] was followed. The diazonium salt was obtained in 90% yield from 2-(*o*-aminobenzoyl)naphthalene prepared by the method of Huisgen and Zahler.[10] The bright orange-yellow powder exhibited infrared bands (Nujol) at 2278 (N_2^+), 1647 (s, CO), and 1050 cm^{-1} (broad, BF).

Procedure for Decomposition of Diazonium Tetrafluoroborates.—All the reactions were replicated and found to be highly reproducible. The products were found to be stable under the reaction conditions.

Run 1.—A solution of 300 mg (1.00 mmole) of 2-diazobenzophenone tetrafluoroborate in 100 ml of 0.10 *N* sulfuric acid[35] was thermostated at 45° for 17 hr. The work-up has been described previously.[7]

Runs 2 and 3.—The procedure was as in run 1 except for the addition of either 100 mg (1.58 mg-atoms) of copper powder (Fisher Scientific) or 120 mg (0.84 mmole, 1.68 mequiv) of cuprous oxide (Baker and Adamson). The reaction time for the cuprous oxide catalyzed reaction was *ca.* 5 min.

Runs 4–11.—The decompositions were carried out at 25° on solutions containing 0.3 mmole of diazonium salt in 30 ml of 0.10 *N* sulfuric acid. Decomposition in the presence of cupric nitrate was carried out with either 265 mg (1.05 mmoles) or 26.5 g (105 mmoles) of cupric nitrate trihydrate (Baker and Adamson) added. Run 11 was performed with 8.50 g (100 mmoles) of sodium nitrate (Fisher Scientific) added to a solution containing 265 mg (1.05 mmoles) of cupric nitrate trihydrate.

Run 12 was performed in dioxane as solvent.

Run 13.—A suspension of 295 mg (0.89 mmole) of 2-(*o*-diazobenzoyl)naphthalene tetrafluoroborate in 25 ml of 4.0 *N* sulfuric acid was heated at reflux for 1 hr with stirring.[36] The regular work-up procedure was employed.

Runs 14 and 15.—To 100 ml of 4.0 *N* sulfuric acid at either 100 or 65° were added, in rapid succession and with stirring, 2 g (32 mg-atoms) of copper powder (Baker and Adamson) and 120 mg (0.36 mmole) of the diazonium tetrafluoroborate. Regular work-up followed.

Runs 16, 18–20.—Suspensions of 0.3–0.5 mmole of salt in 100 ml of acid were used. Decomposition in the presence of cupric nitrate was carried out with 60 g (240 mmoles) of added cupric nitrate trihydrate.

Run 17.—A suspension of 150 mg (0.45 mmole) of the tetrafluoroborate salt in 40 ml of 0.10 *N* sulfuric acid was stirred for 80 hr at 25°. The reaction mixture was then worked up in the usual manner.

Run 21 was a suspension in dioxane.

Decomposition of 2-Diazobenzophenone Tetrafluoroborate in 1.0 *N*, 0.10 *N*, and 0.010 *N* Sulfuric Acid Containing Cupric Nitrate.—The decompositions were carried out at 25° on stirred solutions of 0.4 mmole of diazonium salt in 20 ml of sulfuric acid of the appropriate concentration (1.0 *N*, 0.10 *N*, 0.010 *N*) to which were added 8.0 ml of a solution prepared by dissolving 30 g of cupric nitrate trihydrate (Baker) in 25 ml of water. The catalyst was cuprous oxide (1.68 mequiv). Regular work-up followed. The results are given in Table II.

Decomposition of 2-Diazobenzophenone Tetrafluoroborate in 0.01 *N* Sulfuric Acid in Deuterium Oxide Containing Cupric Nitrate.—The procedure used for decomposition in 0.010 *N* sulfuric acid was replicated with deuterium oxide (Columbia Chemical) being used. The product mixture was analyzed by vpc–mass spectrometry[37] utilizing a column containing 3% OV-17 on Gas-Chrom Q (Applied Science Laboratories). The mass spectra indicated no deuterium incorporation in any of the products.

Decomposition of 2-(*o*-Diazobenzoyl)naphthalene Tetrafluoroborate in 0.10 *N* Sulfuric Acid in Deuterium Oxide.—A suspension of 0.20 mmole of diazonium salt in 20 ml of 0.10 *N* sulfuric acid in deuterium oxide was decomposed by the addition of 0.8 mequiv of cuprous oxide. Analysis of the reaction products by vpc–mass spectrometry combination indicated no deuterium in the products.

***p*-Bromophenol. A. Cuprous Oxide Catalyzed Decomposition.**—To a stirred solution of 243 mg (0.95 mmole) of *p*-bromobenzenediazonium tetrafluoroborate in 100 ml of water containing 60 g (240 mmoles) of cupric nitrate trihydrate (Baker and Adamson) was added cuprous oxide (130 mg, 0.90 mmole, Baker and Adamson). Rapid evolution of nitrogen occurred and a negative β-naphthol test on a drop of the reaction mixture directly after the addition of catalyst indicated that the decomposition was complete. The blue solution was extracted with methylene chloride and the organic extract washed with 0.1 *N* sodium hydroxide. The aqueous layer was acidified with concentrated sulfuric acid and extracted with methylene chloride. The extract yielded 142 mg (87%) of *p*-bromophenol, mp 62–63°. The infrared and nmr spectra were identical with those of authentic material. No material was obtained upon work-up of the base-washed organic layer.

B. Thermal Decomposition.—A solution of 278 mg (1.08 mmoles) of *p*-bromobenzenediazonium tetrafluoroborate in 100 ml of water was heated at reflux for 1 hr at the end of which time a negative β-naphthol test was obtained. The reaction was worked up as above yielding 109 mg (53%) of *p*-bromophenol, mp 60–63°. The base-washed organic layer yielded 76 mg of a brown oil, the infrared spectrum of which indicated that it was a hydrocarbon-like material.

Gas Chromatographic Analysis.—The product mixtures from 2-diazobenzophenone tetrafluoroborate were analyzed on a 6-ft 17.9% Apiezon-L column (on 70/80 Anakrom ABS) at 200° with a helium flow rate of 50 cc/min. Hexadecane (Matheson, Coleman and Bell, 99%) was used as internal standard and the products (commercially available) were all calibrated *vs.* this standard.

The product mixtures from 2-(*o*-diazobenzoyl)naphthalene tetrafluoroborate were analyzed on a 6-ft 5% Carbowax 20M column (on 110/120 Anakrom ABS) with temperature programming from 175 to 240° at 4°/min. The helium flow rate was 100 cc/min. The internal standard used was *o*-fluoro-N,N-dicyclohexylbenzamide[38,39] and all the products (separated by

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[33] E. Noelting, *Ber.*, **37**, 2556 (1904).

[34] J. Lipowitz and T. Cohen, *J. Org. Chem.*, **30**, 3891 (1965).

[35] These are the conditions used by DeTar.[18]

[36] These are the conditions used by Huisgen.[10]

[37] We wish to thank the National Institutes of Health for a grant with which the LKB 9000 combined gas chromatograph–mass spectrometer was purchased. We also thank Dr. Charles Sweeley for his help in obtaining and interpreting the spectra.

[38] Prepared by Dr. J. Lipowitz.[16,39]

[39] J. Lipowitz, Ph.D. Dissertation, University of Pittsburgh, 1964.

column chromatography as described by Huisgen[10]) were calibrated *vs.* the standard.

Registry No.—2-Diazobenzophenone tetrafluoroborate, 14319-50-7; 2-(*o*-diazobenzoyl)naphthalene tetrafluoroborate, 14319-51-8; *p*-bromobenzenediazonium tetrafluoroborate, 14319-52-9.

Catalysis of α-Hydrogen Exchange. VII. Isobutyraldehyde-2-*d* Exchange in the Presence of Primary Amine Salts and Pyridine Buffers[1]

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The dedeuteration of isobutyraldehyde-2-*d* has been studied in the presence of pyridine buffers and the hydrochlorides of ten different primary amines. The principal term in the kinetic equation has the form $k[\mathrm{Me_2CDCHO}][\mathrm{C_5H_5N}][\mathrm{RNH_3^+}]$ and is believed to be due to the rate-controlling attack of pyridine on N-isobutylidenealkylammonium ions present in equilibrium with aldehyde and alkylammonium ions. With RNH_3^+ such that R is primary, the catalytic efficiency tends to increase with increasing acidity (decreasing basicity of RNH_2), but isopropyl- and *t*-butylammonium ions are less reactive than would be expected from their acidities. The effect of the structure of R on the reactivity is discussed in terms of the hybridization of and the charge on the nitrogen atom to which R is attached in the alkylammonium ion, the imine, and the transition state of the rate-controlling step and also in terms of steric factors.

In previous papers in his series the dedeuteration of isobutyraldehyde-2-*d* catalyzed by tertiary amines and oxygen bases has been studied[3] and evidence has been described that catalysis of this dedeuteration by methylammonium ions involves the intermediate formation of the conjugate acid of N-isobutylidenemethylamine, which is then attacked by base to give an enamine in the rate-controlling step of the reaction.[1b,4,5] In order to learn more about the effect of structure on reactivity in deuterium exchange *via* the iminium ion mechanism, we have studied the catalytic action of other amine hydrochlorides in the presence of pyridine buffers.

Results

The rate of loss of deuterium from isobutyraldehyde-2-*d* was followed by nmr measurements of the type used previously. Within any given run the reaction was found to obey the first-order rate equation (eq 1) where AD represents isobutyraldehyde-2-*d*.

$$-\frac{d[\mathrm{AD}]}{dt} = k_p[\mathrm{AD}] \qquad (1)$$

If the reaction mechanism given in Scheme I is operative and equilibrium between aldehyde and iminium ion is established rapidly relative to the deuterium exchange reaction, so that the steps governed by k_B and k_B' are rate controlling, then the first-order rate constants k_p obtained in individual runs may be expressed as in eq 2,[1b,3-5] where K is the equilibrium

$$k_p = \sum_i k_{B_i}[B_i] + \frac{KK_{RNH_3}[RNH_3^+]}{K_{IH}} \sum_i k_{B_i}'[B_i] \qquad (2)$$

constant for the formation of the imine from aldehyde and amine, K_{RNH_3} is the acidity constant of the ammonium ion, K_{IH} is the acidity constant of the iminium ion, k_B is the rate constant for the attack of a given base on the deuterioaldehyde, and k_B' is the rate constant for the attack of the same base on the deuterioiminium ion. Unless otherwise stated, the rate and equilibrium constants used are not the "true" values based on the concentration of free aldehyde but are apparent constants based on the total concentration of aldehyde (free and hydrated).

SCHEME I

$$\mathrm{Me_2CDCHO} + \mathrm{B} \xrightarrow{k_B} \mathrm{Me_2C{=}CHO^-} + \mathrm{BD}$$

$$\mathrm{RNH_3^+} \overset{K_{RNH_3}}{\rightleftharpoons} \mathrm{RNH_2} + \mathrm{H^+}$$

$$\mathrm{Me_2CDCHO} + \mathrm{RNH_2} \overset{K}{\rightleftharpoons} \mathrm{Me_2CDCH{=}NR} + \mathrm{H_2O}$$

$$\mathrm{Me_2CDCH{=}NR} + \mathrm{H^+} \overset{1/K_{IH}}{\rightleftharpoons} \mathrm{Me_2CDCH{=}NHR^+}$$

$$\mathrm{Me_2CDCH{=}NHR^+} + \mathrm{B} \xrightarrow{k_B'} \mathrm{Me_2C{=}CHNHR} + \mathrm{BD}$$

In the current studies the bases in the solutions were pyridine, water, hydroxide ions, amine (the conjugate base of the ammonium salt used), isobutyrate ions (from isobutyric acid present as an impurity in the aldehyde used), and imine. It has already been shown that a plot of the logarithms of the rate constants for the attack of various bases on isobutyraldehyde-2-*d* *vs.* the logarithms of the rate constants for the attack of the same bases on the N-methyliminium ion of isobutyraldehyde-2-*d* gives a fairly straight line.[1b] We have assumed that one iminium ion will resemble another at least as much as either resembles an aldehyde and therefore that the relative reactivities of bases toward the iminium ions derived from isobutyraldehyde and any of the primary ammonium ions investigated will be about the same as toward the N-methyliminium ion. On the basis of this assumption and previous observations,[1b,3-5] it may be shown that catalysis by water, hydroxide ions, imine, and

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[1] (a) This investigation was supported in part by Public Health Service Grants 06829 MCB and AM 10378 from the National Institute of Arthritis and Metabolic Diseases. (b) For the preceding paper in this series, see J. Hine, J. Mulders, J. G. Houston, and J. P. Idoux, *J. Org. Chem.*, **32**, 2205 (1967).

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[3] J. Hine, J. G. Houston, J. H. Jensen, and J. Mulders, *J. Am. Chem. Soc.*, **87**, 5050 (1965).

[4] J. Hine, B. C. Menon, J. H. Jensen, and J. Mulders, *ibid.*, **88**, 3367 (1966).

[5] J. Hine, F. C. Kokesh, K. G. Hampton, and J. Mulders, *ibid.*, **89**, 1205 (1967).