take place, not important in this catalytic reaction. At this stage, it would be worthwhile to refer to the similar cobalt-catalyzed reaction of nitric oxide and BH_4^- with styrene to give actophenone oxime.[34] Nitric oxide also has the characteristics of a free radical, and, in spite of the fact that it is a good ligand in transition-metal chemistry, no catalytic reaction of nitric oxide via migratory insertion process was ever known.[35] These results support the activation of hydrocarbons instead of a small molecule such as molecular oxygen or nitric oxide. Since the activation of oxygen is not important in the present catalytic oxygenation, the model reactions of cytochrome P-450 by the catalysis of Mn(TPP)X[3,4] needs further examination as to whether or not the activation of molecular oxygen is really involved during the course of reaction. Although Mn(OAc)(TPP) gave epoxide and alcohol from olefin and saturated hydrocarbons, respectively, the epoxidation of alkene and hydroxylation of alkane could be a reaction of alkenes or alkanes with generated hydroperoxide by the catalysis of Mn(OAc)(TPP).[36] Porphyrin complexes such as Mn(OAc)(TPP) or Fe(TPP)Cl likewise catalyzed the decomposition of 7 in the presence of BH_4^-, but contrary to Co(TPP), Mn(OAc)(TPP) did not show a catalytic effect for the reduction of acetophenone, which suggests a unique character of Mn(TPP)X.

It is noteworthy at this point that in the overall catalytic oxygenation, cobalt complex catalyzes at least three elementary reactions, that is, generation of an alkyl cobalt complex which subsequently reacts with dioxygen, decomposition of hydroperoxide or its derivative, and hydrogenation of ketone. It exemplifies the multifunctional behavior of transition-metal species in the redox reaction.

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Phase-Transfer-Catalyzed Gomberg-Bachmann Synthesis of Unsymmetrical Biarenes: A Survey of Catalysts and Substrates

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Two problems have hindered the Gomberg-Bachmann (GB) and Pschorr reactions of arenediazonium cations: the instability of the arenediazonium salts and side reactions. Arenediazonium tetrafluoroborate and hexafluorophosphate salts can be prepared in high yield and purity and can be stored safely. Unfortunately, these salts are insoluble in most nonpolar organic solvents. Crown ether complexation or other phase-transfer (pt) catalytic methodology can ameliorate this situation, and reactions conducted by the approaches outlined herein often afforded coupling or cyclization products in high yield and corresponding purity. The use of crown ethers, quaternary 'onium salts, lipophilic carboxylic acid salts, and even the polar cosolvent acetonitrile increase the utility of the ptGB reaction dramatically. Sixty examples of couplings are reported along with an assessment of selectivities. A number of examples are also presented of phase-transfer-type Pschorr cyclizations. In the latter case, the use of potassium superoxide, KO_2, is introduced to suppress indazole formation.

The so-called Gomberg-Bachmann reaction can be traced to the report of Mohlau and Berger in 1893[1] that anhydrous benzenediazonium chloride reacts with pyridine to afford 18% 2-phenylpyridine along with a smaller amount of the 4-isomer. The reaction is generally dated, however, from 1924 when Gomberg and Bachmann showed that anhydrous arenediazonium compounds were not required and that "diazonium salts in aqueous solution, under certain conditions, can couple with hydrocarbons and many diverse derivatives therefrom...".[2] The advantage of the Gomberg-Bachmann (GB) approach (eq 1) is

$$ArN_2^+ + HO^- \xrightarrow{Ar'H/H_2O} ArAr' \qquad (1)$$

that the "powerfully explosive"[2] dry diazonium salts did not have to be utilized, rather the salt could be formed in a normal diazotization reaction and then used directly in situ.

The advent of the phase-transfer method and the observation that macrocyclic (crown) polyethers can solubilize stable, solid arenediazonium tetrafluoroborates[3] have brought the method full circle by allowing one to avoid some of the complicating side reactions associated with the standard GB reaction. We have previously reported that considerably improved yields can be realized in this reaction by application of the phase-transfer technique.[4] We now report experimental details of these reactions and a survey that outlines the scope and utility of this modification.

Results and Discussion

Advantages of the Phase-Transfer Method. The phase-transfer Gomberg-Bachmann (ptGB) modification allows safe, stable arenediazonium tetrafluoroborates to be used in aromatic hydrocarbon solvents in the absence of water, thus avoiding some of the side reactions that have historically complicated this reaction. The ptGB reaction is conducted at room temperature by stirring the ArN_2^+-BF_4^- or -PF_6^- salt in an aromatic hydrocarbon solvent with solid KOAc and a phase-transfer catalyst for 1-2 h. Our early work involved only crown ethers as catalysts, but

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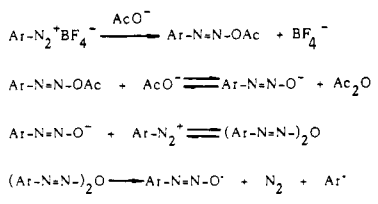
0022-3263/84/1949-1594$01.50/0

Scheme I



other systems work as well (see below).

The ptGB procedure offers a safe, convenient method for the preparation of unsymmetrical biarenes and generally affords these compounds in higher yields than traditional, two-phase procedures. Obviously, an additional isolation step is required compared to the more conventional Gomberg–Bachmann–Hey[5] procedure, but recent methodology[6] makes the aniline-to-diazonium salt conversion nearly quantitative and routine for many substrates. Moreover, the diazotization reaction must be done in any case, and the present procedure allows an opportunity for careful purification at this stage if desired.

Mechanism of the Reaction. Much literature has accumulated on the GB reaction mechanism since its discovery,[7] but the scheme proposed by Ruchardt and Merz[8] now seems firmly established (see Scheme I). We have obtained no evidence to suggest that the mechanism is significantly altered under phase-transfer conditions.

In the presence of KOAc, a metathetical gegenion exchange takes place (BF_4^- for AcO^-) resulting in formation of the transient diazoacetate. It is in this step, we believe, that crown plays a critical role by complexing both the insoluble diazonium and K^+ salts and bringing them together in the nonpolar solvent.

Two other aspects of the mechanism seem important. The first is that the aryl radical which forms does not isomerize: the unpaired electron is attached to the carbon that originally bore the amino function. This means that a single product results when the arene solvent is symmetrical. The second aspect is that although the reaction may involve diazo anhydrides [$(ArNN)_2O$] and nitroxide radicals ($ArNNO\cdot$), ultimately, each ArN_2^+ salt affords a radical, making the theoretical yield 100% rather than 50%. Note also that according to the Ruchardt mechanism[8] 2 equiv of AcO^- are required for the reaction.

Survey of the ptGB Reaction. The results of our survey of the ptGB reaction between sixty different arenediazonium salt/arene solvent combinations are recorded in Table I. All reactions were conducted by stirring the ArN_2BF_4 salt (6 mmol), KOAc (12 mmol), and 18-crown-6 catalyst (5 mol %) in the indicated solvent (60 mL) for ca. 90 min at ambient temperature. After evaporation of the solvent and alumina filtration chromatography, the pure biarene was obtained. Occasionally, an additional chromatography or short path (Kugelrohr) distillation was required. Product distributions were then determined by gas–liquid chromatographic analysis. Pure compounds, when previously unreported, were obtained by preparative GC, sometimes on larger scale reaction mixtures.

It is evident from the data in Table I that the ptGB reaction is successful for a wide variety of arenediazonium salts and arene solvents. In some cases, the yield improvement using the ptc method over previous literature reports is dramatic (see entries 1, 2, and 6 in Table I, for example). It is not surprising that when benzene is the arene cosolvent, a single product is formed and yields are good. They range from ca. 40% for the ortho-substituted (which often give poorer yields than their para-substituted counterparts) salts to as high as 80% for several examples. Note that a very poor yield (2%) is obtained from 2-methylbenzenediazonium tetrafluoroborate (entry 42). This is due to indazole formation (74%, see below). The yield of the desired biarene may be increased to 30% in this case by substituting K_2CO_3 for KOAc (see below).

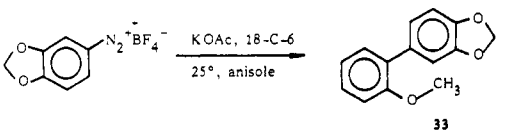
Reactions with *p*-xylene (entries 38, 58) and mesitylene (entries 27, 39) also afforded single products due to the solvents' symmetry. No product was detected that might have resulted from abstraction of benzylic hydrogen. We did note, however, that coupling of 4-methyl salt **13** with toluene (entry 45, Table I) resulted in a biarene product mixture contaminated by 2% of bibenzyl.

Arylation of furan (entries 32, 40, 46, 59) and thiophene (entries 9, 33, 41, 60) occurred in generally good yield and exclusively at the 2-position. In contrast, arylation of pyridine (entries 10, 13, 16, 34, 47) gave mixtures of all three possible products. For example, 4-chloro salt **7** reacted with pyridine to give a biarene mixture (55%) composed of 58%, 31%, and 11% of the 2-, 3-, and 4-substituted products, respectively. It should be noted that Abramovitch and Saha[9] have observed similar reactions of arenediazonium salts initiated by pyridine at 75 °C. Since the latter reaction likely proceeds by a mechanism different from Scheme I, it is not clear how relevant their results are to our own.

Selectivity in the ptGB Reaction. Mixtures of *o*-, *m*-, and *p*-biarene isomers result when the aryl radicals react with monosubstituted benzene derivatives. The ortho isomer predominates in all cases. The formation of mixtures under these conditions diminishes the synthetic value of this method, although many widely used arylation reactions also yield product mixtures. Pure products can be obtained by careful distillation[10] or recrystallization.[11]

It is interesting that in the cases we have examined, the isomer distribution is indifferent to the catalyst used (see below and Table III). This suggests that an aryl radical is formed under either phase-transfer or classical conditions.

Among the monosubstituted solvents used as coupling substrates, methyl benzoate and anisole both afforded high ortho selectivities. This selectivity allowed us to prepare the interesting, steroid-shaped biarene **33** in 23% overall yield after crystallization (eq 2).



(2)

33

Catalysts Other Than Crown Ethers. Shortly after our preliminary report of the ptGB reaction, Bartsch and Yang[12] showed that the reaction could be catalyzed by glymes. In addition, our finding that gegenion metathesis involving quaternary ammonium salts[13] could be used to solubilize ArN_2^+ compounds and the report[14] of soap-ac-

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Table I. Survey of the Phase-Transfer Gomberg-Bachmann Unsymmetrical Biarene Synthesis

entry	compd	substituent[d]	solvent	yield,[b] %	% 2[c]	% 3[c]	% 4[c]	mp,[d] °C	lit.[e] yield	lit.[f] mp, °C
1	1	H	benzene	62	na	na	na	69	22[5]	70[5]
2	1	H	fluorobenzene	68	59	31	10	73-74	nr	73.5[37]
3	1	H	chlorobenzene	75	85	14	1	34	33[38]	34[5]
4	1	H	bromobenzene	60	75	25	0	oil	nr	oil[39]
5	1	H	iodobenzene	0	na	na	na	na	nr	oil[39]
6	1	H	anisole	55	91	2	7	29	15[40]	29[40]
7	1	H	benzonitrile	63	60	14	26	26-36.5	nr	37[41]
8	1	H	methyl benzoate	29	80	7	13	113-114	nr	114-115[42]
9	1	H	thiophene	43	100	0	na	42-43	11[2]	42-43[2]
10	1	H	pyridine	51	78	15	7	oil	40[43]	oil[1]
11	2	2-F	benzene	42	na	na	na	73-74	nr	73.5[37]
12	2	2-F	methyl benzoate	2	83	8	9	oil	nr	nr
13	2	2-F	pyridine	27	75	20	5	oil	nr	nr
14	3	3-F	benzene	74	na	na	na	26-26.5	nr	26-27[37]
15	3	3-F	methyl benzoate	34	90	4	6	oil	nr	nr
16	3	3-F	pyridine	37	68	23	9	oil	nr	oil[44]
17	4	4-F	benzene	60	na	na	na	73-73.5	nr	74[37]
18	4	4-F	chlorobenzene	49	85	14	1	oil	nr	nr
19	4	4-F	bromobenzene	41	68	23	9	oil	nr	nr
20	4	4-F	anisole	34	69	19	12	oil	nr	nr
21	4	4-F	benzonitrile	42	70	10	20	64-65	nr	nr
22	5	2-Cl	benzene	73	na	na	na	34-34.5	38[5]	34[5]
23	6	3-Cl	benzene	79	na	na	na	oil	27[2]	oil[2]
24	6	3-Cl	anisole	48	75	12	13	oil	nr	nr
25	7	4-Cl	benzene	80	na	na	na	76-77	40[5]	77[5]
26	7	4-Cl	toluene	39[g]	72	12	16	29-30	nr	29.5-30[45]
27	7	4-Cl	mesitylene	55	100	0	0	64-65	nr	nr[46]
28	7	4-Cl	fluorobenzene	58	59	31	10	41-41.5	nr	nr
29	7	4-Cl	chlorobenzene	74	65	20	15	oil	nr	oil[47]
30	7	4-Cl	anisole	45	74	13	8	57-57.5	nr	58[45]
31	7	4-Cl	benzonitrile	58	51	14	35	113-115	nr	nr
32	7	4-Cl	furan	75	100	0	na	73-74	29[48]	74-75[48]
33	7	4-Cl	thiophene	62	100	0	na	81-82.5	33[49]	83[49]
34	7	4-Cl	pyridine	55	58	31	11	51-52	37[50]	52-53[50]
35	8	3,4-Cl_2	benzene	53	na	na	na	49-50	nr	49-50[51]
36	9	2-Br	benzene	81	na	na	na	oil	nr	oil[39]
37	10	4-Br	benzene	81	na	na	na	90	44[5]	90[5]
38	10	4-Br	*p*-xylene	26	100	0	0	oil	nr	nr
39	10	4-Br	mesitylene	53	100	0	0	69-72	nr	72-73[52]
40	10	4-Br	furan	55	100	0	na	85-86	15[48]	85-86[48]
41	10	4-Br	thiophene	56	100	0	na	99-100	20[2]	100[2]
42	11	2-Me	benzene	2[h]	na	na	na	oil	8[53]	oil[53]
43	12	3-Me	benzene	58	na	na	na	oil	28[53]	oil[53]
44	13	4-Me	benzene	73	na	na	na	46-47	22[43]	46[43]
45	13	4-Me	toluene	27[i]	70	16	12	oil	19[53]	oil[53]
46	13	4-Me	furan	74	100	0	na	oil	35[54]	oil[54]
47	13	4-Me	pyridine	50	62	38[j]		oil	nr	oil[55]
48	14	3,4-Me_2	benzene	50	na	na	na	oil	29	oil[56]
49	14	3,4-Me_2	fluorobenzene	45	53	47[j]		oil	nr	nr
50	14	3,4-Me_2	chlorobenzene	55	66	21	13	oil	nr	nr
51	14	3,4-Me_2	bromobenzene	60	63	26	11	oil	nr	nr
52	15	4-Et	benzene	50	na	na	na	33-34	nr	33-34[57]
53	15	4-Et	chlorobenzene	45	58	28	14	oil	nr	nr[58]
54	16	4-MeO	benzene	80	na	na	na	89	25[5]	89[5]
55	17	3,5-MeO_2	benzene	50	na	na	na	61-62	nr	61-62[59]
56	18	2-NO_2	benzene	38	na	na	na	37-38	45[43]	37[43]
57	19	4-NO_2	benzene	85	na	na	na	114	60[5]	114[2]
58	19	4-NO_2	*p*-xylene	44	100	0	0	87	nr	nr[59]
59	19	4-NO_2	furan	30	100	0	na	134-134.5	20[48]	134-135[48]
60	19	4-NO_2	thiophene	38	100	0	na	136-137	23	137-138[2]

[a] Substituent on benzenediazonium tetrafluoroborate. [b] Isolated yield of pure biarene based on the diazonium salt. [c] Product distributions determined by GC analysis. [d] Melting point of the major isomer. [e] Best available literature (i.e., highest) yields for synthesis of the biarene by a GBH reaction. [f] In °C. [g] No bibenzyl detected by GC analysis. [h] The major product (74%) was indazole. [i] Product mixture contaminated by 2% bibenzyl. [j] Isomers could not be separated by GC. na = not applicable. nr = not reported.

celerated azo coupling reactions prompted us to attempt the ptGB reaction with catalysts other than crown ethers.[15] The results of these studies are recorded in Table II.

Generally, crown ether catalysis proved best, but in some cases results were only marginally better than with other catalysts. Aliquat 336 was as effective as crown as were Bu_4NHSO_4 and $PhCH_2NEt_3Cl$, but rates were slow with the latter two. The addition of a small amount of acetonitrile as a cosolvent was as effective as using crown catalysis, and this modification of the GB reaction is probably the best to date.[15]

Potassium hexanoate and hexadecanoate are interesting reagents for this reaction since they serve two purposes

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Table II. Biarene Syntheses Using Catalysts Other Than Crown Ethers[a]

substituent	catalyst	mol %[b]	equiv of KOAc	yield, % 1.5 h[c]	yield, % 24 h[d]
4-CH_3O			2	4	
4-CH_3O	18-C-6	5	2	80[d]	80
4-CH_3O	$PhCH_2N(C_2H_5)_3Cl$	5	2	49	60
4-CH_3O	$(n\text{-}C_4H_9)_4NHSO_4$	5	2	54	87
4-CH_3O	$(C_8H_{18}\text{-}C_{10}H_{22})_3NCH_3Cl$[e]	5	2	79	71
4-CH_3O	$K^+{}^-O_2C(CH_2)_4CH_3$	200	0	75	68
4-CH_3O	$K^+{}^-O_2C(CH_2)_{14}CH_3$	200	0	53	67
4-CH_3O	CH_3CN	5	2	68	76
4-CH_3O	CH_3CN	10	2	72	69
2-Br	18-C-6	5	2	81	
2-Br	$(n\text{-}C_4H_9)_4NHSO_4$	5	2		51
2-Cl	18-C-6	5	2	73	
2-Cl	$(n\text{-}C_4H_9)_4NHSO_4$	5	2	60[d]	
2-Cl	$K^+{}^-O_2C(CH_2)_4CH_3$	200	0	23	26
2-Cl	$K^+{}^-O_2C(CH_2)_{14}CH_3$	200	0	44	42
2-Cl			2	30	

[a] The arenediazonium salt was stirred in benzene at ambient temperature for the indicated time period in the presence of the specified additives. [b] mol % of additive relative to arenediazonium compound. [c] Yield determined by GC analysis unless otherwise specified. [d] Yield is for isolated, pure material. [e] Trade name Aliquat 336.

Table III. Comparison of Isomer Distribution[a] with Different Catalysts in the Coupling Reaction between 4-Chlorobenzenediazonium Tetrafluoroborate and Chlorobenzene[b]

catalyst	% 2	% 3	% 4
none[c]	65	16	19
18-C-6[d] + KOAc[e]	65	20	15
BTEAC[d,f] + KOAc[e]	67	19	14
TBAB[d,g] + KOAc[e]	69	18	13
potassium hexanoate[e]	65	18	17
5% CH_3CN + KOAc[e]	63	17	20

[a] Yields determined by GC analysis. Estimated accuracy is ±3%. [b] Reaction time 90 min unless otherwise specified. [c] Reaction time 24 h. [d] 5 mol % relative to ArN_2BF_4. [e] 2 equiv. [f] BTEAC = $PhCH_2NEt_3Cl$. [g] TBAB = Bu_4NHSO_4.

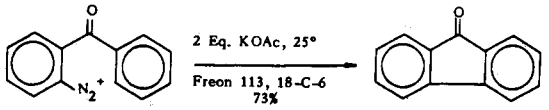
in the reaction. First, each presumably acts as a pt agent by forming a soluble diazoester, ArNNOCOR. This can then react with another acid salt, $M^+{}^-OCOR$, to give $ArNNO^-$, which reacts with ArN_2^+ to afford ArNNONNAr (see line 2 of Scheme I).

The reaction of 4-chlorobenzenediazonium tetrafluoroborate with chlorobenzene was surveyed by using different catalysts to see if selectivity was altered. The results are summarized in Table III and show that the selectivity is not, within experimental error, affected by this variable.

Nature of the Arene Solvent. Since these reactions involve, at least in their early stages, reactions of ionic species, it seemed reasonable to expect that solvent polarity[16] or Lewis basicity[17] would play some role in the reaction rate. We therefore allowed $4\text{-}ClC_6H_4N_2BF_4$ to react with benzene, thiophene, chlorobenzene, anisole, or benzonitrile for 90 min at ambient temperature under the usual conditions (see Experimental Section). The extent of these reactions respectively are 5%, 7%, 38%, 72%, and 100%. These values were determined as extent of reaction = (yield without catalyst/yield with catalyst) × 100%.

Phase-Transfer Diazonium Ion Ring-Closure Reactions. We hoped to elaborate our success with the ptGB reaction into an alternative method for ring closure related to the Pschorr cyclization.[18] Our attempts to cyclize two arenes connected by various bridges in Cl_2FCCF_2Cl (Freon 113) is summarized in Table IV. The phase-transfer method was found to be as useful as the classical methods for preparing the fluorenone and phenanthrene ring systems and better than any previously reported cyclization conducted under basic, rather than acidic,[18,19] conditions.

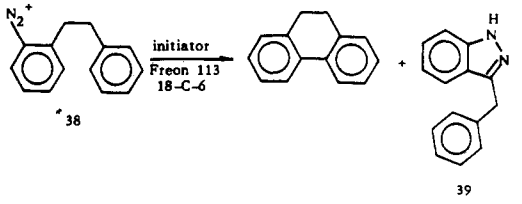
The reaction is conducted by stirring the arenediazonium tetrafluoroborate salt with an initiator like KOAc in an inert solvent. As noted above, we have used $F_2ClC\text{-}CFCl_2$ as solvent for this reaction since the normal arene solvents would couple and therefore be unacceptable. Obvious choices like $CHCl_3$ and CCl_4 are precluded because of their ability to serve as either hydrogen or chlorine atom donors. An example of the intramolecular coupling reaction is shown in eq 3. In this example, fluorenone is



(3)

isolated in 73% yield. The copper powder/H_2SO_4 method[19] afforded the same compound in 71% yield, but when conducted under basic conditions,[20] only 20% product was obtained.

One particular attempted reaction deserves special note. We hoped to develop a general synthesis of biphenyl-substituted crown ethers by utilizing this macrocyclization. It was hoped that the presence of an additional cation (as in the form of $NaBF_4$) might template[21] the cyclization as illustrated in eq 4. Unfortunately, only protodediazoniation occurred.[22]



(4)

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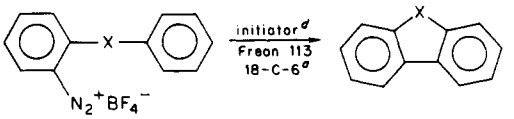
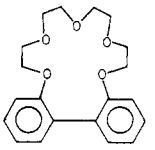
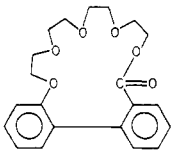
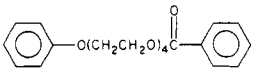
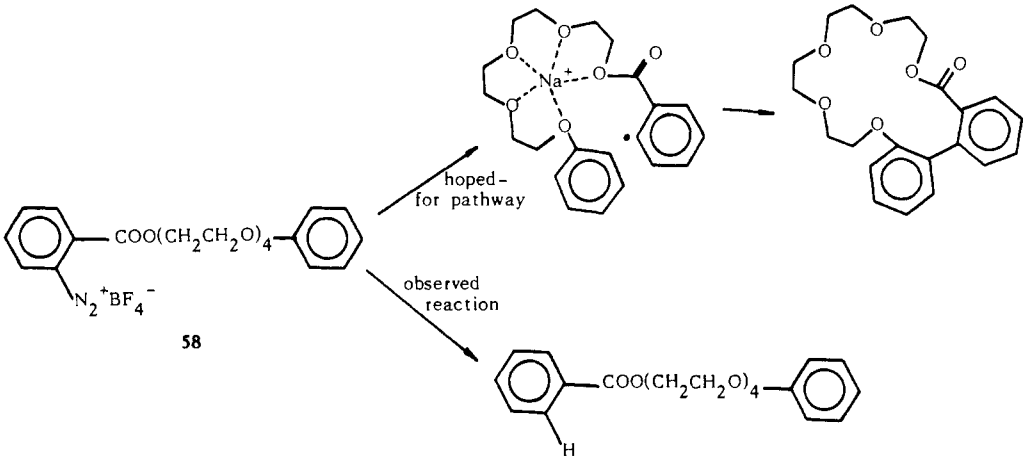
Table IV. Phase-Transfer-Catalyzed Pschorr-Type Cyclization Reactions



X	initiator (equiv)	cyclized product	yield,[c] %	lit. yield, %	other products[b] (yield)
C(O)	KOAc (2)	fluorenone	73	71[19]	
CH=CH(COOH)	KOAc (3)	phenanthrene-9-carboxylic acid	80	86[20]	
CH_2CH_2	KOAc (2)	9,10-dihydrophenanthrene	trace	32[31]	3-benzylindazole (55%)
CH_2CH_2	K_2CO_3 (1)	9,10-dihydrophenanthrene	0	5[a]	no reaction
CH_2CH_2	KO_2 (1)	9,10-dihydrophenanthrene	37	5[a]	
$(CH_2)_4$	KOAc (2)	dibenzo[a,c]cyclooctane	0	3[31]	3-(3-phenylpropyl)indazole (36%)
$(CH_2)_4$	KO_2 (1)	dibenzo[a,c]cyclooctane	0	5[a]	
O	KOAc (2)	dibenzofuran	0	45[60]	
S	KOAc (2)	dibenzothiophene	9	40[61]	
$O(CH_2CH_2O)_4$	NaOAc (10)		0		
$O(CH_2CH_2O)_4C(O)$	NaOAc (10)		0		

[a] All reactions were performed in the presence of 5-10 mol % of 18-crown-6 except the last two. [b] If the normal cyclized product was not formed, other isolable products are identified. [c] Isolated yield of pure material. [d] The arenediazonium salt, initiator, and crown catalyst were stirred at ambient temperature in 1,1,2-trichloro-1,2,2-trifluoroethane (Freon 113) until decomposition of the diazonio function was complete.

Scheme II



In some cases, superoxide (KO_2) initiated cyclizations were superior to those mediated by KOAc. This is presumably because indazole formation is suppressed in these cases (see below).

Indazole Formation: Superoxide and Carbonate as Initiators. When coupling of 2-$CH_3C_6H_4N_2BF_1$ with benzene was attempted (see entry 42, Table I), indazole formation (74%) predominated over coupling (2%).[23] We attributed this difficulty to the basicity of KOAc. When acetate was replaced in this reaction by trifluoroacetate, 40% of indazole was obtained, but 13% of the coupling product was produced. No indazole was formed when CO_3^{2-} was used as base and 30% of the desired biarene was produced. This was something of a surprise since the nucleophilicity of carbonate is relatively low and its basicity is clearly higher than that for F_3CCOO^-. The reaction is illustrated in (Scheme II).

Indazole formation was also a problem in the attempted pt Pschorr reaction. It occurred to us that superoxide might be a useful reagent in this context since it could, in principle at least, form a radical directly that would decompose with loss of oxygen and nitrogen to give the desired aryl radical. The presumed mechanism is illustrated in eq 5. Attempted cyclization of 2-diazoniobibenzyl using

$$Ar^+N{\equiv}N + {}^-OO\cdot \rightarrow ArNNOO\cdot \rightarrow Ar\cdot \qquad (5)$$

KOAc as base afforded 3-benzylindazole in 55% yield. No reaction was observed when K_2CO_3 was substituted for KOAc, but 37% 9,10-dihydrophenanthrene was obtained when KO_2 was used as initiator. Clearly, the Cu^0/H^+ coupling methods[24] have advantages in cases where inda-

(23) Behr, L. C.; Fusco, R.; Jarboe, C. H. "Pyrazoles, Pyrazolines, Pyrazolidines, Indazoles and Condensed Rings"; Wiley, R. H., Ed.; Interscience: New York, 1967; Chapter 10.

(24) Abramovitch, R. A. *Adv. Free-Radical Chem.* **1966**, *2*, 89.

zole formation is a problem, but when acid sensitive groups are present, the KO_2-initiated coupling procedure may be of value. To our knowledge this is the first application of superoxide in reactions of this sort, although there has been considerable interest in this reagent in recent years.[25]

Summary

$ArN_2^+ BF_4$ and PF_6 salts are now available in high yield and purity and are quite stable. Their lack of solubility in common organic solvents has prevented their utilization in many synthetic transformations. We have shown above that application of phase-transfer conditions to certain of these reactions makes them much more useful than they have proved to be historically. Phase-transfer conditions make the Gomberg–Bachmann reaction a useful method for the synthesis of various unsymmetrical biarenes. The most selective approach is to couple a substituted arenediazonium salt to a symmetrical arene solvent, but considerable selectivity is also possible when the arene has nonequivalent coupling positions available.

Intramolecular cyclization is also possible in a phase-transfer variant of the Pschorr reaction. This affords a neutral to slightly basic method for ring closure of aryl radicals which affords yields similar to those for the best Cu^0/H^+-mediated conditions and generally far superior to previously published basic conditions.

Finally, we introduce potassium superoxide, KO_2, as a useful reagent for the pt Pschorr and ptGB reactions. In the latter case, the reagent is most useful when indazole formation reduces coupling yields.

Experimental Section

Melting points (uncorrected) were determined (Mel-Temp or Thomas Hoover) in open capillaries. Infrared (IR) spectra (in cm^{-1}) (Perkin-Elmer Model 281) were recorded on neat samples and calibrated at 1601 cm^{-1} (polystyrene). Proton NMR spectra (in δ) were recorded (Varian Model EM 360) as ~10% solutions in $CDCl_3$ (Me_4Si internal standard).

18-Crown-6 was prepared as previously reported.[26] All other solvents and reagents were AR grade or better and were used without further purification. Preparative chromatography columns were packed with MCB activated alumina (80–325 mesh, chromatographic grade, AX611).

Arenediazonium Salts. All arenediazonium tetrafluoroborate salts in this section were prepared from commercially available amines by Roe's method[6a] in aqueous HCl or HBF_4. Immediately prior to use, the salts were reprecipitated from Me_2CO with Et_2O and then air-dried.

Phase-Transfer Synthesis of Unsymmetrical Biarenes. General Reaction and Isolation Procedure. KOAc (1.20 g, 12.2 mmol, 2 equiv) was added at ambient temperature to a magnetically stirred mixture of ArN_2BF_4 (6.00 mmol) and 18-crown-6 (5 mol %) in 60 mL of the solvent. Stirring was continued for 90 min. The red mixture was filtered and the filtrate washed with brine and water. The organic layer was dried over Na_2SO_4 and evaporated, and the residue was chromatographed over alumina (30–50 g). Occasionally an additional distillation was required to remove colored impurities. When the product was an isomer mixture, the major isomer was collected by preparative GC (Varian 920, TC detector, 10 ft × 0.25 in. 10% Carbowax 20M on 80–100 mesh NAW Chromosorb P column). Typically ca. 100 mg of the pure isomer was collected for complete characterization.

GC Analysis of Biarene Isomer Mixtures. Isomer distributions (Table I) were determined by using a Varian Model 1420 gas chromatograph (thermal conductivity detector), 10 ft × 0.125 in. 10% Carbowax 20M on 80–100 mesh NAW Chromosorb P column, flow rate of ca. 20mL/min of He, oven temperature between 210 °C and 270 °C. Isomers eluted in the order ortho, meta, para. Peak areas were determined on a DuPont Model 310 curve resolver with an estimated accuracy of ±3%.

2-(2-Fluorophenyl)pyridine (20). Compound **2** (1.28 g, 6 mmol) was stirred with KOAc (1.20 g, 12 mmol) and 18-crown-6 (0.08 g, 5 mol %) in pyridine (60 mL) for 90 min as described in the general procedure. Column chromatography (10% ether/hexane) afforded a yellow oil (0.29 g, 27%). The product was a mixture of isomers (see Table I). A GC prep sample of **20** had the following properties: oil; NMR 7.2–7.5 (m, 4 H), 7.8–8.2 (m, 3 H), 8.80 (d, 1 H, J = 4 Hz); IR 1590, 1210, 755. Anal. Calcd for $C_{11}H_8FN$: C, 76.29; H, 4.66; N, 8.09. Found: C, 76.18; H, 4.30; N, 8.29.

3′-Fluorobiphenyl-2-carboxylic Acid, Methyl Ester (21). Compound **3** (1.28 g, 6 mmol) reacted (as above) with methyl benzoate (60 mL). After chromatography (10% ether/hexane) and distillation (125–130 °C/0.05 torr) **21** and its isomers were obtained (0.48 g, 34%). Pure **21** (GC prep) had the following properties: oil, NMR 3.57 (s, 3 H), 6.8–7.4 (m, 7 H), 7.7–7.8 (m, 1 H); IR 1720, 1285, 875, 755. Anal. Calcd for $C_{14}H_{11}FO_2$: C, 69.75; H, 3.90. Found: C, 70.03; H, 3.97.

2-Bromo-4′-fluorobiphenyl (22). Compound **4** (1.28 g, 6 mmol) reacted as above with bromobenzene (60 mL). Chromatography (hexane) afforded an oil (0.64 g, 41%). Pure **22** had the following properties: oil; NMR 6.90–7.71 (m, 8 H); IR 1600, 1505, 1220, 830, 750. Anal. Calcd for $C_{12}H_8BrF$: C, 57.40; H, 3.21. Found: C, 57.66; H, 3.22.

4′-Fluoro-2-methoxybiphenyl (23). Compound **4** (1.28 g, 6 mmol) reacted (as above) with anisole (60 mL). Chromatography afforded a colorless oil (0.42 g, 34%). Pure **23** was isolated by GC: oil; NMR 3.80 (s, 3 H), 6.70–7.52 (m, 8 H); IR 2910, 1230, 740. Anal. Calcd for $C_{13}H_{11}FO$: C, 77.21; H, 5.48. Found: C, 76.95; H, 5.37.

2′-Cyano-4-fluorobiphenyl (24). Compound **4** (1.28g, 6 mmol) reacted (as above) in benzonitrile (60 mL). After distillation (120–124 °C/0.05 torr) a mixture of isomers was obtained (0.50 g, 42%). Pure **24** was isolated by prep GC: mp 64–65 °C; NMR 6.90–7.82 (m, 8 H); IR 2110, 1475, 830, 765. Anal. Calcd for $C_{13}H_8FN$: C, 79.17; H, 4.10; N, 7.10. Found: C, 78.79; H, 3.99; N, 6.83.

3′-Chloro-2-methoxybiphenyl (25). Compound **6** (1.38g, 6 mmol) reacted (as above) with anisole (60mL). Chromatography (hexane) yielded a colorless oil (0.64 g, 48%). Pure **25** was isolated by GC: oil; NMR 3.77 (s, 3 H) 6.75–7.40 (m, 8 H); IR 1455, 1230, 1015, 740. Anal. Calcd for $C_{13}H_{11}ClO$: C, 71.40; H, 5.07. Found: C, 71.47; H, 5.06.

4′-Chloro-2-fluorobiphenyl (26). Compound **7** (1.38 g, 6 mmol) reacted (as above) with fluorobenzene (60 mL). Chromatography (hexane) afforded an oil (0.72 g, 58%). Pure **26** was isolated by GC: mp 41–41.5 °C; NMR 6.95–7.77 (m, 8 H, sharp peak at 7.53); IR 1910, 1580, 1210, 810, 750. Anal. Calcd for $C_{12}H_8ClF$: C, 69.75; H, 3.90. Found: C, 69.56; H, 3.68.

4′-Chloro-2-cyanobiphenyl (27). Compound **7** (1.38g, 6 mmol) reacted (as above) with benzonitrile (60mL). Distillation (120–127 °C/0.05 torr) gave a colorless solid (0.76 g, 58%, mp 60–72 °C). Pure **27** was isolated by GC: mp 113–115 °C; NMR 7.27–7.90 (m, 8 H, sharp peak at 7.53); IR 2210, 1455, 825, 765. Anal. Calcd for $C_{13}H_8ClN$: C, 69.75; H, 3.90. Found: C, 69.56; H, 3.68.

4′-Bromo-2,5-dimethylbiphenyl (28). Compound **10** (1.63 g, 6 mmol) reacted (as above) with *p*-xylene (60 mL). Chromatography (hexane) afforded **28** as a pale yellow oil: 0.41 g, 26%; NMR 2.25 (s, 3 H), 2.38 (s, 3 H), 7.05–7.82 (m, 7 H, sharp peaks at 7.17, 7.30, 7.53, and 7.67); IR 1490, 1010, 830, 810. Anal. Calcd for $C_{14}H_{13}Br$: C, 63.41; H, 6.46. Found: C, 63.23; H, 6.52.

Mixture Including 3,4-Dimethyl-2′-fluorobiphenyl. Compound **14** (1.34 g, 6 mmol) reacted (as above) with fluorobenzene (60 mL). Chromatography (hexane) yielded a colorless oil (0.55 g, 45%). The isomers were not separable by GC. The isomer mixture had the following properties: NMR 2.30 (s, 6H), 6.80–7.53 (m, 7H); IR 1485, 1220, 760. Anal. Calcd for $C_{14}H_{13}F$: C, 83.97; H, 6.54. Found: C, 84.21; H, 6.56.

2′-Chloro-3,4-dimethylbiphenyl (29). Compound **14** (1.34 g, 6 mmol) reacted (as above) with chlorobenzene (60 mL). Chromatography (hexane) yielded a colorless oil (0.73 g, 55%). Pure **29** was collected by GC prep: oil; NMR 2.32 (s, 6 H),

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7.15–7.32 (m, 7 H); IR 1030, 880, 820, 750, 660. Anal. Calcd for $C_{14}H_{13}Cl$: C, 77.59; H, 6.05. Found: C, 77.31; H, 6.04.

2′-Bromo-3,4-dimethylbiphenyl (30). Compound **14** (1.34 g, 6 mmol) reacted (as above) with bromobenzene (60mL). Chromatography (hexane) afforded a colorless oil (0.79 g, 60%). Pure **30** had the following properties: oil; NMR 2.30 (s, 6 H), 7.08–7.70 (m, 7 H); IR 1460, 1020, 815, 750, 740. Anal. Calcd for $C_{14}H_{13}Br$: C, 64.39; H, 5.02. Found: C, 64.65; H, 5.06.

2-Chloro-4′-ethylbiphenyl (31). Compound **15** (1.34 g, 6 mmol) reacted (as above) with chlorobenzene (60mL). Chromatography (hexane) afforded a mixture of biphenyl isomers (0.60 g, 45%). Pure **31** was isolated from the mixture as an oil; NMR 1.20 (t, 3 H, J = 7 Hz), 2.65 (q, 2 H, J = 7 Hz), 7.23 (s, 8 H); IR 1455, 1030, 745 cm^{-1}. Anal. Calcd for $C_{14}H_{13}Cl$: C, 77.59; H, 6.05. Found: C, 77.45; H, 6.01.

2,5-Dimethyl-4′-nitrobiphenyl (32). Compound 19 (1.20 g, 12 mmol) reacted (as above) with *p*-xylene (60 mL). Chromatography (10% ether/hexane) afforded an off-white solid, which was recrystallized (95% EtOH) to afford pure **32**: (0.60 g, 44%); mp 87–88 °C; NMR 2.25, 2.38 (s, s, 6 H), 7.03–7.30 (m, 3 H), 7.43, 7.60 (AB, 24, J = 10 Hz); 8.45, 8.62 (AB, 24, J = 10 Hz); IR 1595, 1510, 1350, 850. Anal. Calcd for $C_{14}H_{13}NO_2$: C, 73.99; H, 5.76; N, 6.16. Found: C, 73.98, H, 5.80; N, 5.90.

2′-Methoxy-3,4-(methylenedioxy)biphenyl (33). KOAc (7.50 g, 0.076 mol) was added in a single portion to a mechanically stirred mixture (90 min) of 3,4-(methylenedioxy)benzenediazonium tetrafluoroborate[10] (11.00 g, 0.036), 18-crown-6 (0.20 g), and anisole (300 mL) in a 500-mL flask. After filtration, rotary evaporation, and chromatography, the product and its isomers were obtained as a colorless oil (4.51 g, 55%), which was crystallized from 90% EtOH. Pure **33** was obtained as white needles, mp 55–56 °C (lit.[27] mp 56–57 °C); NMR 3.73 (s, 3 H), 5.87 (s, 2 H), 6.51–7.13 (m, 7 H).

Catalysts Other Than 18-Crown-6: Materials. Potassium hexanoate and hexadecanoate were prepared by treatment of the corresponding carboxylic acids with 20% aqueous KOH in toluene followed by azeotropic removal of the water. All other catalysts were obtained from commercial sources.

Catalysts Other Than 18-Crown-6: Table II. The arenediazonium salts (0.01 mol) were stirred in benzene (100 mL) at ambient temperature in the presence of the specified additives for the indicated time. After filtration, the reaction mixtures were concentrated in vacuo and then toluene was added to the residue to a volume of 5.00 mL. Yields were obtained by integration of GC peaks obtained from injections (equal volumes) of these solutions and standard (2.0 M) solutions of the biphenyls.

Effect of 18-Crown-6 Catalyst in Solvents Other Than C_6H_6: General Reaction Procedure. Reactions run to completion were performed as follows: KOAc (0.20 g, 0.4 mmol) was added to a magnetically stirred mixture of 4-chlorobenzenediazonium tetrafluoroborate (0.45 g, 0.2 mmol), 18-crown-6 (0.026 g, 0.1 mmol), and 20 mL of the appropriate aromatic solvent. After being stirred 90 min, the reactions were filtered and the solvent was removed by rotary evaporation (except benzonitrile which was removed by Kugelrohr distillation) to leave the crude red oil. Reactions not run to completion were conducted in the same manner except 18-crown-6 was omitted.

Effect of 18-Crown-6 Catalyst in Solvents Other Than C_6H_6: General GC Analysis Procedure. Each crude product mixture from the above reactions was dissolved in toluene and adjusted to a volume of 2.00 mL. Three 5-μL samples of each mixture were injected into a Varian Model 1420 gas chromatograph equipped with a 6 ft. × 0.125 in. 5% SE-30 on Chromosorb P 80–100 mesh column. The average peak area for the three runs was determined. In cases where more than one isomer was produced, only the largest peak was measured. Extent of reaction was calculated according to the following equation:

$$\frac{\text{peak area (yield) without catalyst}}{\text{peak area (yield) with catalyst}} \times 100 = \text{extent of reaction}$$

Reaction of 4-Chlorobenzenediazonium Tetrafluoroborate (7) with Chlorobenzene under Various Conditions (See Table III). Compound **7** (1.38 g, 6 mmol) and chlorobenzene (60 mL) were allowed to react at ambient temperature for 90 min, unless otherwise noted, in the presence of the additives specified in Table III. Workup and GC analysis were accomplished as described in the general procedure for Table I.

2-Benzoylbenzenediazonium Tetrafluoroborate (34). A 500-mL flask was charged with 2-aminobenzophenone (3.28 g, 17 mmol), 95% EtOH (50 mL), and 48% HBF_4 (6.50 mL, 46 mmol). The yellow solution was stirred vigorously at −5 °C. Ice-cold amyl nitrite (2.15 g, 18.4 mmol) was added dropwise (some precipitate formed). After 30 min, cold Et_2O (200 mL) was added and the solution was stirred 30 min more. The salt[28] was filtered, washed with Et_2O, and air-dried: yield, 4.47 g, 93%; mp 101.5–102 °C dec; IR (mull) 2280, 1660, 1150–1000, 735, 700.

Cyclization of 34 to Fluorenone. A 250 mL, three-necked flask was charged with **34** (1.68 g, 6 mmol), 18-crown-6 (0.08 g, 5 mol %), and Freon 113 (100 mL). KOAc (1.27 g, 12 mmol) was added in a single portion and stirred at ambient temperature for 12 h. After filtration, no ArN_2^+ salts remained ($C_6H_5NMe_2$ color test) and the solvent was evaporated to leave an oil, which solidified after chromatography (Al_2O_3, Et_2O/hexanes). The crude fluorenone was obtained (0.79 g, 73%) as a yellow solid, mp 83–84 °C (lit.[29] mp 83–83.5 °C).

***trans*-2-(Diazonium tetrafluoroborate)-α-phenylcinnamic Acid (37).** *trans*-2-Nitro-α-phenylcinnamic acid (**35**) was obtained (4.55 g, 64%, mp 196–198 °C, lit.[18] mp 195–196 °C) by using the procedure of Pschorr.[18] Compound **35** (1.20 g, 4.4 mmol) was reduced at 80 °C with granular Sn (5 g) and concentrated HCl (20 mL) to give the corresponding amine hydrochloride (**36**·HCl), mp 218–220 °C (lit.[18] mp 218 °C).

The hydrochloride of **36** (0.30 g, 1.1 mmol) was dissolved in 95% EtOH (10 mL) and 48% HBF_4 (3 mL). To the cooled mixture (0 °C) was added cold isoamyl nitrite (0.17 g, 1.5 mmol) dropwise. After stirring 15 min, Et_2O (25 mL) was added and the yellow product was collected and then dissolved in Me_2CO with the aid of a little DMF. Slow addition of Et_2O yielded **37** (0.32 g, 88%) as bright yellow plates: mp 87 °C (violent dec!); IR (mull) 2290, 1700, 1100–1000, 770.

Cyclization of 37. A 250-mL flask was charged with **37** (2.00 g, 6 mmol), Freon 113 (60 mL), KOAc (1.27 g, 12 mmol), and 18-crown-6 (0.16 g, 10 mol %) and the mixture stirred at ambient temperature for 24 h. A solution of 10% NaOH (50 mL) was added and the aqueous layer washed (2 ×25mL Et_2O) and acidified with 6 N HCl. Phenanthrene-9-carboxylic acid (1.06 g, 80%) crystallized and was recrystallized from 95% EtOH: mp 153–156 °C. (lit.[30] mp 156.5–157 °C).

Synthesis of 2-(2-Phenylethyl)benzenediazonium Tetrafluoroborate (38). 2-Nitrostilbene was prepared by LiOMe (1.5g Li in 60 mL of MeOH) mediated Wittig reaction between benzyltriphenylphosphonium chloride (70.2 g, 0.18 mol) and 2-nitrobenzaldehyde (27.3 g, 0.18 mol) in DMF (300 mL) at 90 °C for 16 h. After dilution with H_2O (600 mL), extraction with Et_2O (2 × 200 mL), and drying (Na_2SO_4), the solution was evaporated and the residue chromatographed (Al_2O_3, 5% Et_2O/hexane) to give the 2-nitrostilbene isomer mixture (27.6 g, 68%) as a pale yellow oil, which solidified on standing.

The isomer mixture (1.73 g, 7.7 mmol) was hydrogenated (60 psi) in the presence of 10% Pd/C (0.1 g) to 2-aminobibenzyl (1.39 g, 92%) as a colorless solid, mp 31–32 °C (lit.[31] mp 33 °C).

A 250-mL flask was charged with 2-aminobibenzyl (3.02 g, 12 mmol), 95% EtOH (30 mL), and 48% aqueous HBF_4 (7 mL). The solution was cooled to −5 °C, and isoamyl nitrite (1.4 g, 12 mmol) was added dropwise. After 30 min (the solution turned cloudy), cold Et_2O (200 mL) was added, and stirring was continued an additional 30 min. The precipitate was collected by filtration, and pure **38** (2.35 g, 66%) was obtained by reprecipitation from Me_2CO: mp 45–47.5 °C (dec); IR (Nujol mull) 2270, 750.

KOAc-Mediated ptPschorr Reaction of 38: Synthesis of 3-Benzylindazole (39). KOAc (1.20 g, 12 mmol) was added to

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(31) Ibuki, E.; Ozasa, S.; Fujioka, Y.; Okada, M. *Yakugaku* Zasshi **1980**, *100*, 718.

a stirred mixture of **38** (1.80 g, 6 mmol), 18-crown-6 (0.08 g, 5 mol %), and Freon 113 (60 mL). After stirring vigorously overnight, **39** (0.69 g, 55%) was isolated by filtration, washing with CH_2Cl_2, and recrystallization from petroleum ether, mp 112–113.5 °C (lit.[32] mp 113–115 °C).

Attempted K_2CO_3-Mediated ptPschorr Reaction of 38. K_2CO_3 (0.84 g, 6 mmol) was added to a stirred mixture of **38** (1.80 g, 6 mmol) and 18-crown-6 (0.08 g, 5 mol %) in Freon 113 (60 mL). IR analysis of the reaction mixture after 24 h of vigorous stirring revealed unreacted diazonium salt. Evaporation of the solvent left ca. 200 mg of an uncharacterized dark oil.

KO_2-Mediated Cyclization of 38. Powdered KO_2 (0.43 g, 6 mmol), **38** (1.80 g, 6 mmol), and 18-crown-6 (0.16 g, 10 mol %) were stirred together for 2 days at ambient temperature in Freon 113 (60 mL). Gas chromatographic analysis of the product mixture after filtration, evaporation, and chromatography (alumina, hexane) showed 9,10-dihydrophenanthrene (**40**, 73%), bibenzyl, and another byproduct (27%). Crystallization from MeOH afforded pure **40** [0.40 g, 37%, mp 34–35 °C (lit.[31] mp 34.5–35 °C)].

Preparation of 2-(4-Phenylbutyl)benzenediazonium Tetrafluoroborate (41). A solution of (3-chloropropenyl)benzene (Aldrich, 5.00 g, 33 mmol) and Ph_3P (8.66 g, 33 mmol) was stirred in refluxing toluene (50 mL). Pure cinnamyltriphenylphosphonium chloride (**42**, 11.04 g, 80%) was collected by filtration: mp 225–226 °C (lit.[33] mp 224–226 °C).

A 100-mL flask was charged with **42** (9.89 g, 24 mmol), 2-nitrobenzaldehyde (3.26 g, 24 mmol) and DMF (30 mL) and the mixture heated at 90 °C. A solution of LiOMe (0.17 g of Li dissolved in 20 mL of dry MeOH) was added during 10 min and the mixture stirred an additional 30 min. After cooling, the solution was poured into H_2O (300 mL), extracted with Et_2O (2 × 200 mL), dried over Na_2SO_4, and evaporated to a red oil. 1-(2-Nitrophenyl)-4-phenylbutadiene (**43**, 4.92 g, 81%) was isolated as yellow needles, mp 88–90 °C, after chromatography (alumina, 10% Et_2O/hexane): NMR 6.80–7.13 (m, 4 H); 7.23–8.03 (m, 9 H); IR (KBr) 1520, 1335, 780. Anal. Calcd for $C_{16}H_{13}NO_2$: C, 76.48; H, 5.21; N, 5.37. Found: 76.18; H, 5.16; N, 5.66.

Hydrogenation of **43** (4.50 g, 18 mmol) over 10% Pd/C (50 psi) for 2 h provided 1-(2-aminophenyl)-4-phenylbutane (**44**) as a colorless oil[31] (4.05 g, 100%).

A 250-mL flask was charged with **44** (2.70 g, 12 mmol), 95% EtOH (30mL), and 48% aqueous HBF_4 (7 mL). The solution was cooled to −5 °C, and cold isoamyl nitrite (1.42 g, 12 mmol) was added. After 30 min of stirring, Et_2O (150 mL) was added and precipitated **41** (2.29 g, 85%) was collected: mp 71–73 °C dec; IR (mull) 2300, 1470, 1050, 710.

Attempted KOAc-Mediated Cyclization of 41: Formation of 3-(3-Phenylpropyl)indazole. KOAc (0.72 g, 7.4 mmol), **41** (1.20 g, 3.7 mmol), and 18-crown-6 (0.05 g) were stirred together in Freon 113 (50 mL) for 2 days. After filtration, evaporation, chromatography (alumina, 1:1 ether/hexane), and distillation (Kugelrohr, 130 °C, 0.075 torr), 3-(3-phenylpropyl)indazole (0.31 g, 36%) was obtained as a colorless oil: NMR 2.00–3.23 (m, 6 H), 6.93–7.80 (m, 9 H), 11.5–12.0 (br s, 1 H); IR 3450–3000, 1620, 1495, 740. Anal. Calcd for $C_{16}H_{16}N_2$: C, 81.32; H, 6.82; N, 11.85. Found: C, 81.16; H, 6.99; N, 11.88.

Attempted KO_2-Mediated Cyclization of 41. KO_2 (0.85 g, 12 mmol), **41** (1.94 g, 6 mmol), and 18-crown-6 (0.08 g, 5 mol %) were stirred overnight in Freon 113 (60 mL). TLC analysis of the tarry residue obtained after workup as described above indicated no cyclization product had formed.

Synthesis of 2-Phenoxybenzenediazonium Tetrafluoroborate (45). 2-Nitrodiphenyl ether[34] (7.82 g, 36 mmol) in absolute EtOH (30 mL) was hydrogenated (55 psi) in the presence of 10% Pd/C for 6 h. 2-Aminodiphenyl ether (**46**, 6.02 g, 99%) was isolated as a light brown oil:[34] NMR 3.25 (br s, 2 H), 6.75–7.23 (m, 9 H).

A 250-mL flask was charged with **46** (3.70 g, 20 mmol), 95% EtOH (30 mL), and 48% aqueous HBF_4 (7 mL). The solution was cooled to −5 °C and isoamyl nitrite (2.34 g, 20 mmol) was added dropwise. After 20 min, Et_2O (150 mL) was added and precipitated **45** (4.94 g, 87%) was collected: mp 111–111.5 °C dec; IR (mull) 2290, 1290, 1050, 770; NMR [$(CD_3)_2CO$] 7.10–7.73 (m, 7 H), 8.07 (t, 1 H), 8.70 (d, 1 H).

Attempted Cyclization of 45. KOAc (1.20 g, 12 mmol), **45** (1.73 g, 6 mmol), 18-crown-6 (0.08 g, 5 mol %), and Freon 113 (60mL) were stirred overnight and then filtered, and the solvent was evaporated. TLC analysis (silica, 10% ether/hexane) of the tarry residue indicated that no dibenzofuran was present.

2-Thiophenoxybenzenediazonium Tetrafluoroborate (47). 1-Chloro-2-nitrobenzene (8.50 g, 54 mmol) was treated with potassium thiophenoxide (8.02 g, 54 mmol) in DMF (70 mL) to afford 2-nitrophenyl phenyl sulfide (**48**, 11.72 g, 94%); mp 53–54 °C (lit.[35] mp 54.4 °C).

Compound **48** (5.00 g, 22 mmol) was reduced with tin (6.5 g) and concentrated HCl (30 mL) to give 2-aminophenyl phenyl sulfide hydrochloride (**49**, 2.92 g, 55%): mp 232–233 °C (lit.[35] mp 233.5 °C).

Compound **49** (2.50 g, 10 mmol) was diazotized in ice-cold EtOH (10 mL) with 48% HBF_4 (4 g) and isoamyl nitrite (1.23 g, 11 mmol) to provide a pale yellow solid: 2.34 g (78%); IR (mull) 2275, 1050 (br), 750.

Cyclization of 47. A 250-mL flask was charged with **47** (0.90 g, 3 mmol), 18-crown-6 (40 mg), and Freon 113 (30 mL) and then KOAc (0.60 g, 6 mmol) was added. Stirring was continued for 24 h, and the solution was filtered, evaporated, and chromatographed (alumina, hexane) to afford dibenzo[*a*,*c*]thiophene as a white solid: 50 mg (9%); mp 98–100 °C (lit.[36] mp 99–100 °C).

Nitration of Bis[2-(2-phenoxyethoxy)ethyl] Ether. A 1-L flask was charged with bis[2-(2-phenoxyethoxy)ethyl] ether[35] (26 g, 75 mmol) and Ac_2O (300 mL) and cooled to ca. 10 °C. Nitric acid (6.75 g, 75 mmol) was added over 5 min, and the mixture was stirred overnight without additional cooling. The solution was poured into H_2O (600 mL), made basic with solid NaOH, extracted with CH_2Cl_2 (2 × 250 mL), dried (Na_2SO_4), evaporated, and chromatographed (alumina, 0–10% ether/hexane, second UV active band) to afford (21.4 g, 73%) a mixture of ortho and para mononitrated ethers.

2-[2-[2-[2-(Aminophenoxy)ethoxy]ethoxy]ethoxy]ethoxybenzene (50). The entire mixture (see above) was hydrogenated (60 psi 10% Pd/C, 0.50 g) for 12 h. After Celite filtration, removal of the solvent left an oil, which was chromatographed (alumina, 0–10% ether/hexane, first UV active band) to afford **50** (3.61 g, 20%) as a colorless oil: NMR 3.50–4.27 (m, 18 H, tall peak at 3.67), 6.60–7.47 (m, 9 H); IR 3450, 3330, 1495, 1105 (br), 740. Anal. Calcd for $C_{20}H_{27}NO_5$: C, 66.46; H, 7.53; N, 3.87. Found: C, 66.67; H, 7.80; N, 3.62.

2-[2-[2-(2-Phenoxyethoxy)ethoxy]ethoxy]ethoxybenzenediazonium Tetrafluoroborate (51). A solution of **50** (5.0 g, 14 mmol) in 48% HBF_4 (25 mL) was cooled to 0 °C, and a solution of $NaNO_2$ (0.97 g, 14 mmol) in cold H_2O (10 mL) was added over 10 min. The solution was stirred for 15 min, extracted (CH_2Cl_2, 30 mL), dried (Na_2SO_4), and evaporated to leave a red oil. The oil was dissolved in CH_2Cl_2 (2 mL) and precipitated by addition of Et_2O. Oily **51** (2.30 g, 36%) had an IR absorption (2250 cm^{-1}) characteristic of the diazonium group. This material was used for the cyclization attempt without further purification.

Attempted Cyclization of 51. The red oil **51** described above (ca. 2 g, 4 mmol) was slurried with powdered $NaBF_4$ (20 g) in CH_2Cl_2. The solvent was evaporated in vacuo to leave a powder, which was then covered with Freon 113 (150 mL) and stirred vigorously. NaOAc (3.5 g, 40 mmol) was added and stirred at ambient temperature for 2 days. After filtration, the solid was washed with CH_2Cl_2 and evaporated in vacuo. TLC analysis (silica, 50% ether/hexane) of the tarry residue did not show the presence of a potentially isolable polyether compound.

2-[2-[2-[2-(Benzyloxy)ethoxy]ethoxy]ethoxy]ethanol (52). A 1-L flask was charged with THF (250 mL) and tetraethylene glycol (97 g, 0.5 mol). Potassium *tert*-butoxide (56 g, 0.5 mol) was added in small portions, and the solution was heated to reflux. Benzyl chloride (63.2 g, 0.5 mol) was added during 1 h, and stirring was continued at reflux for 12 h. After filtration and evaporation, the crude product was distilled through a 10-cm Vigreux column to yield pure **52** (49 g, 52%) as a colorless oil: bp 170–174 °C (25

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torr); NMR 3.10 (br s, 1 H), 3.70 (m, 16 H), 4.55 (s, 2 H), 7.22 (s, 5 H).

2-[2-[2-[2-(Benzyloxy)ethoxy]ethoxy]ethoxy]ethyl 4-Toluenesulfonate (53). A 250-mL flask was charged with tosyl chloride (19.0 g, 0.10 mol), CH_2Cl_2 (100 mL) and pyridine (16 g, 0.2 mol). A solution of **52** (28.5 g, 0.10 mol) in CH_2Cl_2 (50 mL) was added during 1 h. After stirring 12 h at ambient temperature, water (75 mL) was added. The phases were separated and the organic phase was washed with ice-cold 6 N HCl (2 × 50 mL), water (100 mL), and brine (100 mL). After drying (Na_2SO_4), the CH_2Cl_2 was evaporated. Compound **53** was isolated as a pale yellow oil: 39 g (89%); NMR 2.41 (s, 3 H), 3.70 (m, 16 H), 4.57 (s, 2 H), 7.23 (m, 7 H), 7.62 (d, 2 H).

2-[2-[2-[2-(Benzyloxy)ethoxy]ethoxy]ethoxy]ethoxybenzene (54). A 500-mL flask was charged with **53** (22 g, 0.05 mol) and toluene (250 mL). KOPh (6.6 g, 0.05 mol) was added and the mixture stirred at reflux for 12 h. After cooling, the solution was filtered, washed with brine (100 mL) and H_2O (100 mL), then dried (Na_2SO_4), and evaporated to an oil, which was column chromatographed (alumina, 10% ether/hexane) to afford **54** as an amber oil: 14.6 g (81%); NMR 3.53–4.17 (m, 16 H), 4.53 (s, 2 H), 6.67–7.27 (m, 10 H); IR 1600, 1250, 1150–1100, 695.

2-[2-[2-(2-Phenoxyethoxy)ethoxy]ethoxy]ethanol (55). Compound **54** (5.2 g, 14 mmol) was hydrogenated in absolute EtOH (30 mL) at 60 psi for 12 h in the presence of 10% Pd/C catalyst (0.10 g) and a few drops of concentrated HCl. The mixture was neutralized with solid Na_2CO_3, filtered through Celite, and concentrated in vacuo to an oil, which was distilled (Kugelrohr, 135 °C, 0.10 torr). Alcohol **55** (3.3 g, 87%) was obtained as a colorless oil: NMR 2.77 (br s, 1 H), 3.53–4.23 (m, 16 H), 6.80–7.47 (m, 5 H).

2-[2-[2-[2-(Nitrobenzoyloxy)ethoxy]ethoxy]ethoxy]ethoxybenzene (56). A solution of 2-nitrobenzoyl chloride (1.85 g, 1.1 mmol) in pyridine (0.25 g, 3 mmol) and CH_2Cl_2 (20 mL) was stirred at ambient temperature. A solution of **55** (2.70 mg, 10 mmol) in CH_2Cl_2 (15 mL) was added over 1 h. After 12 h the solution was extracted with 3 N HCl (30 mL), 10% NaOH (30 mL), water (30 mL), and finally with brine (30 mL). The CH_2Cl_2 was evaporated in vacuo and the residue was chromatographed (alumina, 0–10% ether/hexane) to afford **56** as a pale yellow oil: 3.01 g (72%).

2-[2-[2-[2-(Aminobenzoyloxy)ethoxy]ethoxy]ethoxy]ethoxybenzene (57). Nitro compound **56** (2.50, 6 mmol) was hydrogenated in absolute EtOH (25 mL) at (50 psi) for 8 h in the presence of 10% Pd/C catalyst. After filtration through Celite, the solution was concentrated in vacuo to a light brown oil, which was Kugelrohr distilled (180–190 °C, 0.20 torr) to yield **57** (2.10 g, 90%) as a colorless oil: NMR 3.50–3.93 (m, 10 H), 4.07 (m, 4 H), 4.37 (m, 2 H), 6.33–7.33 (m, 8 H), 7.73 (d, 1 H); IR (neat) 3490, 1695, 1250, 1150–1050, 760. Anal. Calcd for $C_{21}H_{27}NO_6$: C, 64.76; H, 6.99; N, 3.60. Found: C, 64.51; H, 7.13; N, 3.42.

2-[2-[2-[2-(Diazonium tetrafluoroborate)benzoyloxy]ethoxy]ethoxy]ethoxybenzene (58). A solution of **57** (2.3 g, 5.9 mmol) in 48% HBF_4 (15 mL) was cooled to 0 °C, and $NaNO_2$ (0.48 g, 7 mmol) in H_2O (2 mL) was added dropwise. The solution was stirred 10 min and then extracted with CH_2Cl_2 (20 mL). The organic layer was dried (Na_2SO_4) and evaporated to a red oil. The oil was dissolved in a small amount of CH_2Cl_2 and precipitated by addition of ether. The oil had an IR absorption (2270 cm^{-1}) characteristic of a diazonium cation, and oily **58** was used in the next step without further purification.

Attempted Cyclization of 58. Diazonium compound **58** (1.3 g, 2.7 mmol) and powdered $NaBF_4$ (ca. 15 g) were slurried with CH_2Cl_2 (50 mL). The CH_2Cl_2 was evaporated to leave a powder, which was then covered with Freon 113 (150 mL). NaOAc (1.8 g, 20 mmol) was added and the mixture stirred 24 h. After filtration, the solid was rinsed with CH_2Cl_2 and the combined organic solutions were evaporated. The residue was chromatographed (alumina, hexane) to give a small amount of oil, which was identified as 2-[2-[2-(2-benzoyloxyethoxy)ethoxy]ethoxy]-ethoxybenzene by its NMR, IR, and UV spectra: NMR 3.67–3.97 (m, 12 H), 4.17 (t, 2 H), 4.50 (t, 2 H), 6.83–7.53 (m, 8 H), 8.10 (dd, 2 H); IR: 1720, 1100 (br), 750, 710; UV λ_{max} 234 nm.

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Aromatic Acetonylation Promoted by Manganese(III) and Cerium(IV) Salts[1]

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Treatment of aromatic hydrocarbons with acetone and manganese(III) acetate gave rise to arylacetones in yields ranging from 25% with chlorobenzene to 74% with anisole. Cerium(IV) salts were also successfully used as promoters but gave lower yields. The reactions were relatively free of side products except with toluene. Isomer distributions, relative rates, and partial rate factors were determined for acetonylation of anisole, toluene, chlorobenzene, and fluorobenzene. A Hammett plot of the log of the partial rate factors for the manganese(III) system vs. σ-constants gave a slope, ρ, of -2.4 ± 0.3. An isotope effect $k_H/k_D = 3.8$ was observed for the manganese(III)-promoted reaction with acetone-d_6, indicating rate-determining proton loss from acetone. The overall mechanism involves formation and attack of acetonyl radicals onto the aromatic hydrocarbon followed by subsequent oxidative deprotonation of the resulting σ-radical complex. The acetonyl radical exhibits appreciable electron-deficient character in its substitution behavior with aromatic hydrocarbons.

Metal ion promoted oxidative deprotonation methods have been used to generate such carbon radicals as the carboxymethyl,[2,3] acetonyl,[4,5] and nitromethyl[6-8] (eq 1).[9]

$$CH_3X \xrightarrow[Ce(IV)]{Mn(III)\ or} \cdot CH_2X + H^+ \qquad (1)$$

$$X = CO_2H,\ COCH_3,\ NO_2$$

When produced in the presence of suitable alkenes, quite a number of interesting processes have been reported,[2-5,10-12] most resulting from initial attack of the carbon radical onto the π-bond (eq 2). The analogous radical

$$RCH{=}CHR + \cdot CH_2X \rightarrow R\dot{C}HC(R)HCH_2X \qquad (2)$$

generation with aromatic hydrocarbons present has led to aromatic substitution (eq 3), the mechanism of which has

$$ArH + CH_3X \xrightarrow[Ce(IV)]{Mn(III)\ or} ArCH_2X \qquad (3)$$

been studied rather extensively for carboxymethylation[2] and nitromethylation.[6-8] However, the aromatic acetonylation has been described only briefly.[5,13] The purpose of this work was to more thoroughly study the metal ion promoted aromatic acetonylation with an eye toward assessing the polar properties of the acetonyl radical involved.

Experimental Section

Instrumentation. GC analyses were done on a Hewlett-Packard Model 5840A gas chromatograph equipped with a flame ionization detector and capillary inlet system (split mode). The capillary columns used were (1) 30 m × 0.22 mm sp 2100 glass, (2) 10 m × 0.22 mm sp 2100 glass, (3) 10 m × 0.22 mm Carbowax 20 M fused silica, and (4) 30 m × 0.22 mm bonded SE-30 fused

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