worked up, using the previously described procedure used for the chromic acid reactions.

Chromium Trioxide–Pyridine Complex. The reagent was prepared by the method reported by Dauben, Lorber, and Fullerton.[7] The resulting chromium trioxide–pyridine complex (39 g, 0.22 mol) was combined with a solution of the alkyne (0.01 mol) in anhydrous methylene chloride (300 mL) and the mixture allowed to react at 25 °C for 5 days. Anhydrous diethyl ether (200 mL) was added to the reaction mixture, mixed thoroughly, and allowed to stand for 10 min. The solution was decanted from the dark-brown residue, and the residue was washed with three portions (50 mL) of diethyl ether. The combined ether solutions were passed through a column of Florisil (60–200 mesh, 50 g), and the eluate was concentrated (~50 mL) under reduced pressure, using a Büchi Rotavapor. The residual pyridine was extracted with dilute hydrochloric acid, the ether solution dried over anhydrous sodium sulfate, and the remaining ether solvent removed under vacuum.

Pyridinium Chlorochromate in Methylene Chloride (2f). The alkyne (0.01 mol) was added to a mixture of pyridinium chlorochromate (Aldrich Chemical Co., 21.5 g, 0.02 mol) and anhydrous methylene chloride (200 mL), the flask sealed, and the mixture stirred at room temperature for 2 weeks. Anhydrous diethyl ether (200 mL) was added to the reaction mixture, and after 10 min the liquid phase was decanted from the red-brown residue. The residue was washed with three portions (50 mL) of diethyl ether and the combined ether solutions passed through a column of Florisil (60–200 mesh, 50 g). The solvent was removed under reduced pressure on a Büchi Rotavapor.

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Registry No. Diphenylethyne, 501-65-5; 1-phenyl-1-propyne, 673-32-5; 1-phenyl-1-butyne, 622-76-4; 2-decyne, 2384-70-5; 5-decyne, 1942-46-7; 4-octyne, 1942-45-6; 7-tetradecyne, 35216-11-6; diphenylethanedione, 134-81-6; benzoic acid, 65-85-0; 1-phenyl-1,2-propanedione, 579-07-7; 3-phenyl-2-propynal, 2579-22-8; 1-phenyl-1,2-butanedione, 3457-55-4; 4-phenyl-3-butyn-2-one, 1817-57-8; 2-decyn-4-one, 34695-28-8; 5-decyn-4-one, 13882-01-4; 4-octyn-3-one, 7299-56-1; 7-tetradecyn-6-one, 71328-65-9; chromic acid, 7738-94-5; chromyl chloride, 14977-61-8; *tert*-butyl chromate, 1189-85-1; chromium trioxide, 1333-82-0; chromyl acetate, 4112-22-5; pyridinium chlorochromate, 20492-50-6.

Selective Palladium-Catalyzed Vinylic Substitutions with Bromoiodo Aromatics

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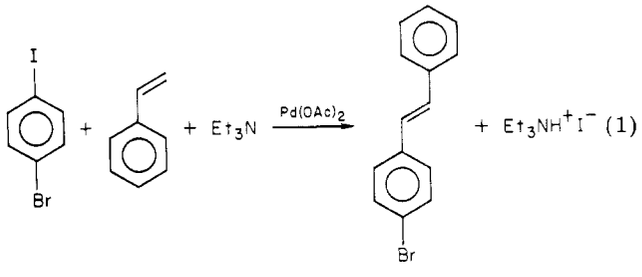
Palladium acetate catalyzed vinylic arylation of olefins occurs selectively at the iodo group of arenes containing both iodo and bromo substituents. Aryl bromides are reactive only if a triarylphosphine is added to the palladium acetate catalyst.

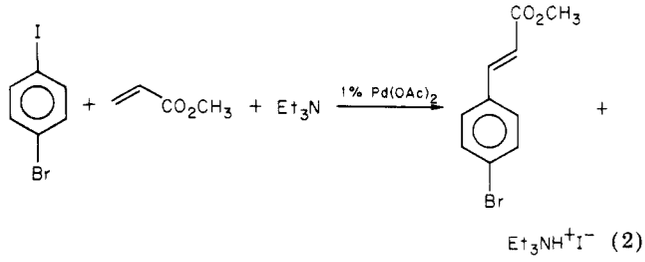
The palladium-catalyzed aryl halide reaction with olefins provides a convenient method for the preparation of 1-aryl olefins.[1] The catalyst required for the reaction depends upon the halide present; aryl iodides require only palladium acetate while aryl bromides do not react unless a triarylphosphine is also present. Therefore, it appeared possible that reactants containing both iodo and bromo groups could be caused to undergo reaction either at the iodo position or at both halo positions. This proved to be possible, and some examples of the reaction are reported herein.

Results and Discussion

4-Bromoiodobenzene is easily prepared by the bromination of iodobenzene.[2] This compound reacts with styrene in the presence of triethylamine and 1 mol % palladium acetate, based upon the organic halide, with acetonitrile as solvent at 100 °C in 17 h to form (*E*)-4-bromostilbene in 64% yield (eq 1). (All yields reported are of purified products.) Similarly, 4-bromoiodobenzene and methyl acrylate react to form (*E*)-methyl 4-bromocinnamate in 5.5 h at 100 °C in 68% yield (eq 2). Further reaction of this



compound with styrene in the presence of a 1% palladium acetate–2% tri-*o*-tolylphosphine catalyst with triethylamine as base produces (*E,E*)-methyl 4-styrylcinnamate in 63% yield (eq 3).



2-Bromoiodobenzene, prepared by the Sandmeyer reaction from 2-bromoaniline, reacted selectively with acrylic

(1) C. B. Ziegler and R. F. Heck, *J. Org. Chem.*, **43**, 2941 (1978), and references therein.
(2) H. Hirtz, *Chem. Ber.*, **29**, 1405 (1896).

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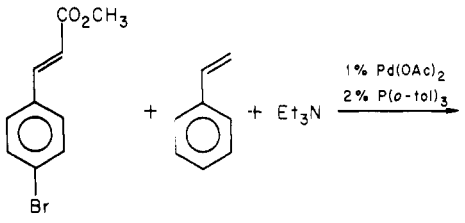
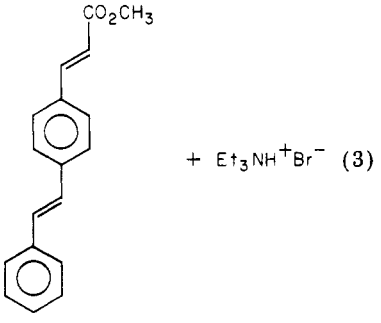
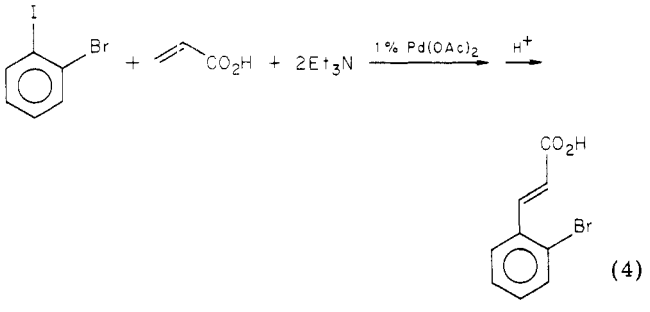
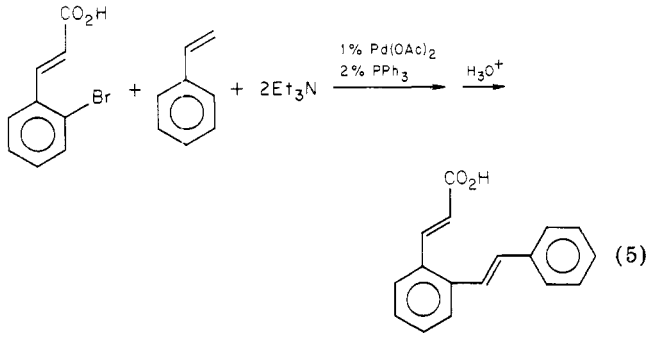




acid, 2 equiv of triethylamine, and 1% palladium acetate at 100 °C in 1 h to produce (*E*)-2-bromocinnamic acid in 82% yield (eq 4). The bromo acid was then reacted with

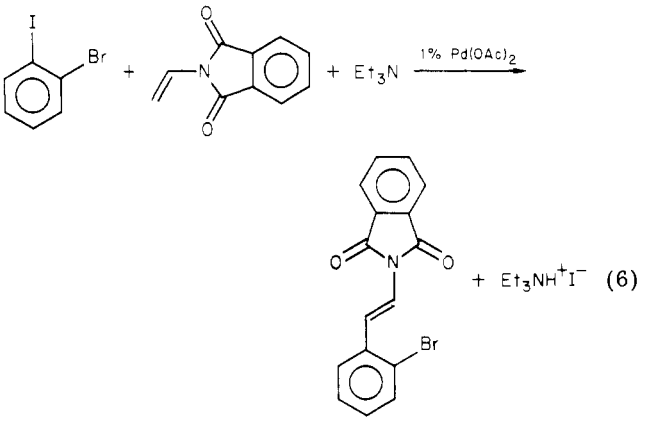


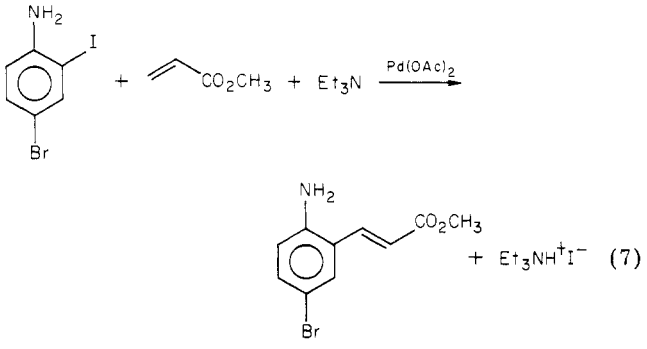
styrene with a palladium acetate–triphenylphosphine catalyst to form (*E,E*)-2-styrylcinnamic acid in 44 h at 100 °C in 20% yield. In these examples the choice of triarylphosphine to be used is not critical,[1] but low yields sometimes result when ortho substituents are present, as in eq 5.



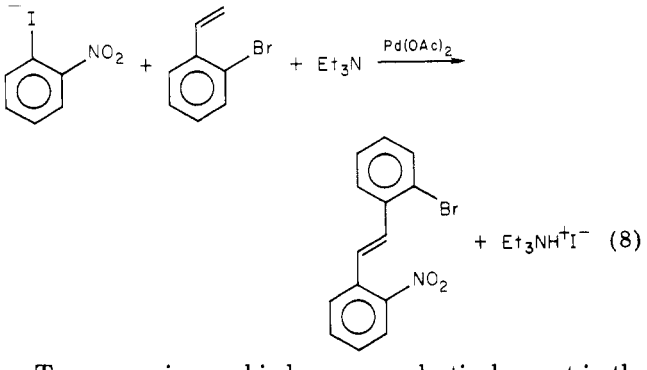
A selective reaction was also observed between 2-bromoiodobenzene and *N*-vinylphthalimide with palladium acetate as catalyst, giving (*E*)-*N*-(2-bromostyryl)phthalimide in 75% yield (eq 6).

Iodination of 4-bromoaniline in the presence of calcium carbonate produces 4-bromo-2-iodoaniline.[3] The iodo group in this compound also reacts selectively with methyl acrylate in the presence of a palladium acetate catalyst at 100 °C in 24 h to afford (*E*)-methyl 2-amino-5-bromocinnamate in 33% yield (eq 7). Highly activated halides such as this one sometimes do not lead to high yields of the desired products.[1]





The iodo and bromo groups can be on different reactants as in the reaction of 2-iodonitrobenzene with 2-bromostyrene. With a palladium acetate catalyst these react at 100 °C in 49 h to form (*E*)-2-bromo-2′-nitrostilbene in 70% yield (eq 8).



To summarize, aryl iodo groups selectively react in the presence of bromo groups with palladium acetate as the catalyst in the vinylic substitution reaction. The bromo groups may then be reacted with another olefin if a palladium acetate–triarylphosphine catalyst is used.

Experimental Section

4-Bromoiodobenzene.[2] A mixture of 16.7 g (0.15 mol) of iodobenzene, 7.7 mL (0.15 mol) of bromine, and a few iron fillings was heated under a reflux condenser on a steam bath until the bromine color had faded. About 4 h were required for the color to be totally dissipated. The mixture partially solidified on cooling, and the solid was separated by filtration. Several recrystallizations from ethanol provided 14.6 g (34%) of colorless crystals of 4-bromoiodobenzene, mp 89–90 °C (lit.[2] mp 92 °C).

(*E*)-4-Bromostilbene. A mixture of 5.66 g (20 mmol) of 4-bromoiodobenzene, 2.5 mL (22 mmol) of styrene, 0.045 g (0.2 mmol) of palladium acetate,[4] 3.1 mL (22 mmol) of triethylamine, and 4 mL of acetonitrile was prepared in a 200-mL heavy-walled Pyrex bottle. The bottle was capped under nitrogen with a self-sealing rubber-lined cap with a small hole in the metal cap for injecting a syringe needle. Gas chromatographic analysis of

(3) F. B. Dains, T. H. Vaughan, and W. M. Janney, *J. Am. Chem. Soc.*, **40**, 930 (1918).

(4) T. A. Stephenson, S. M. Morehouse, A. R. Powell, J. P. Heffer, and G. Wilkinson, *J. Chem. Soc.*, 3632 (1965).

the reaction mixture indicated that the 4-bromoiodobenzene had been completely consumed after 17 h at 100 °C. After being cooled, the reaction mixture was stirred with 100 mL of cold 10% aqueous hydrochloric acid solution. The insoluble solid product which remained was separated by filtration and recrystallized from ethanol to give 3.33 g (64%) of product, mp 135–136.5 °C (lit.[5] mp 135 °C). The NMR spectrum contained a singlet at δ 2.8 and a multiplet at δ 2.1–2.7 in area ratios of 2:9.

(*E*)-Methyl 4-Bromocinnamate. A reaction was carried out as in the above example, substituting 1.98 mL (22 mmol) of methyl acrylate for the styrene. Heating at 100 °C for 5.5 h was sufficient for the consumption of all of the 4-bromoiodobenzene. This product also crystallized upon dilution of the reaction mixture with 100 mL of 10% aqueous hydrochloric acid solution. Recrystallization from ethanol gave 3.27 g (68%) of (*E*)-methyl 4-bromocinnamate: mp 82–84 °C (lit.[6] mp 79–80 °C); NMR δ 7.8–8.2 (m, 5 H), 6.5–6.8 (d, 1 H), 4.0 (s, 3 H).

(*E,E*)-Methyl 4-Styrylcinnamate. A mixture of 2.41 g (10 mmol) of (*E*)-methyl 4-bromocinnamate, 1.4 mL (12.5 mmol) of styrene, 0.023 g (0.1 mmol) of palladium acetate, 0.061 g (0.2 mmol) of tri-*o*-tolylphosphine,[1] and 5 mL of triethylamine was heated in a capped bottle at 100 °C for 2 h. The cooled, solid reaction mixture was broken up with a spatula and stirred with about 200 mL of 10% aqueous hydrochloric acid solution. The insoluble product was collected by filtration, washed with water, and air-dried. Recrystallization from chloroform gave 1.67 g (63%) of product: mp 184–186 °C; mol wt (high-resolution MS) found 264.113, calcd 264.115.

2-Bromoiodobenzene. A solution of 66 mL of concentrated sulfuric acid, 200 mL of water, and 25.8 g (16.4 mL, 0.15 mol) of 2-bromoaniline was cooled to 0 °C in an ice–salt bath (some salt crystallized), and a solution of 10.4 g (0.15 mol) of sodium cyanide in 50 mL of water was added slowly such that the temperature was maintained below 10 °C. The resulting solution of the diazonium salt was added in small portions to a solution of 25 g of potassium iodide and 38 g of iodine in 100 mL of water. The resulting solution was heated under a reflux condenser on a steam bath for 2 h. The excess iodine was reduced by addition of a saturated aqueous solution of sodium sulfite, and the product was extracted from the cooled solution with ether. After being dried, the extracts were distilled, giving 22.8 g (56%) of colorless product: bp 184 °C (1 mm) [lit.[7] bp 257 °C (754 mm)]; NMR δ 8.0–7.5 (m, 2 H), 7.4–6.8 (m, 2 H).

(*E*)-2-Bromocinnamic Acid. A solution of 2.8 g (10 mmol) of 2-bromoiodobenzene, 0.9 mL (12.5 mmol) of acrylic acid, 0.022 g (0.1 mmol) of palladium acetate, 3.5 mL (25 mmol) of triethylamine, and 4 mL of acetonitrile was heated under nitrogen in a capped bottle at 100 °C for 1 h, at which time GLC analysis of the mixture indicated that reaction was complete. After being cooled, the reaction mixture was diluted with 250 mL of 10% aqueous hydrochloric acid solution. The colorless solid obtained was collected by filtration and recrystallized twice from ethanol to give 1.86 g (82%) of product, mp 215–216.5 °C (lit.[8] mp 212–212.5 °C).

(*E,E*)-2-Styrylcinnamic Acid. A mixture of 1.36 g (6 mmol) of (*E*)-2-bromocinnamic acid, 0.52 g (5 mmol) of styrene, 1.75 mL (12.5 mmol) of triethylamine, 11.2 mg (0.05 mmol) of palladium acetate, and 26.2 mg (0.10 mmol) of triphenylphosphine was placed in a Pyrex tube. The air was replaced by argon, and the tube was capped. The two-phase solution was heated for 44 h at 100 °C. After being cooled, the partially solid mixture was diluted with 6 N hydrochloric acid, and the product was extracted with several portions of ether. After the extract was dried, and the solvent removed, the product was recrystallized from ether. There was obtained 0.24 g (20%) of colorless solid: mp 202–204 °C; mol wt (high-resolution MS) found 250.099, calcd 250.099.

(*E*)-*N*-(2-Bromostyryl)phthalimide. A mixture of 5.66 g (20 mmol) of *o*-bromoiodobenzene, 4.33 g (25 mmol) of *N*-vinylphthalimide, 0.045 g (0.20 mmol) of palladium acetate, 3.5 mL (25 mmol) of triethylamine, and 4 mL of acetonitrile under nitrogen in a capped tube was stirred magnetically in a steam bath for 15 h. After being cooled, the mixture was stirred with water and ether, and the insoluble yellow solid was collected by filtration. After recrystallization from benzene there was obtained 4.90 g (73%) of yellow crystals of the product, mp 181–185.5 °C. A second crystallization gave 70% of the purified product: mp 194–195 °C; mol wt (high-resolution MS) found 326.991, calcd 326.989.

(*E*)-Methyl 2-Amino-5-bromocinnamate. 4-Bromo-2-iodoaniline[3] (2.98 g, 10 mmol), 1.12 mL (12.5 mmol) of methyl acrylate, 1.4 mL of triethylamine, 4 mL of acetonitrile, and 0.022 g (0.10 mmol) of palladium acetate were stirred magnetically under argon in a capped Pyrex tube at 100 °C for 24 h. After the mixture cooled, water was added, and the product was extracted with ether. After the extract was dried and the solvent evaporated, a solid was obtained. Recrystallization from ethanol gave 0.84 g (33%) of colorless product, mp 92–93 °C. the mass spectrum of the compound showed a parent peak at *m/e* 255 (calcd *m/e* 255).

The NMR spectrum was as follows: δ 7.75 (d, 2 H, *J* = 16 Hz), 7.5 (d, 1 H, *J* = 2 Hz), 7.2 (dd, *J* = 8 and 2 Hz), 6.6 (d, 1 H, *J* = 8 Hz), 6.3 (d, 1 H, *J* = 16 Hz), 4.1 (br s, 2 H), 3.75 (s, 3 H).

(*E*)-2-Bromo-2′-nitrostilbene. A solution of 4.98 g (20 mmol) of *o*-iodonitrobenzene, 3.2 mL (25 mmol) of *o*-bromostyrene, 3.5 mL of triethylamine, 0.045 g (0.20 mmol) of palladium acetate, and 4 mL of acetonitrile was stirred at 100 °C in a capped tube for 49 h. After being cooled the reaction mixture was stirred with 250 mL of 10% aqueous hydrochloric acid, and the precipitated solid was collected by filtration. After being washed, the product was recrystallized from ethanol twice to give 1.00 g (73%) of yellow crystals of (*E*)-2-bromo-2′-nitrostilbene, mp 106–107 °C. Anal. Calcd for $C_{14}H_{10}BrNO_2$: C, 55.26; H, 3.30. Found: C, 55.40; H, 3.57.

Acknowledgment. Financial support of this research was provided by the National Science Foundation. We are also grateful for the loan of the palladium employed in these reactions from the Matthey-Bishop Co., Inc.

Registry No. 4-Bromoiodobenzene, 589-87-7; iodobenzene, 591-50-4; (*E*)-4-bromostilbene, 13041-70-8; styrene, 100-42-5; palladium acetate, 3375-31-3; (*E*)-methyl 4-bromocinnamate, 71205-17-9; methyl acrylate, 96-33-3; (*E,E*)-methyl 4-styrylcinnamate, 71205-18-0; 2-bromoiodobenzene, 583-55-1; 2-bromoaniline, 615-36-1; (*E*)-2-bromocinnamic acid, 7345-79-1; (*E,E*)-2-styrylcinnamic acid, 71205-19-1; (*E*)-*N*-(2-bromostyryl)phthalimide, 71205-20-4; *N*-vinylphthalimide, 3485-84-5; (*E*)-methyl 2-amino-5-bromocinnamate, 71205-21-5; 4-bromo-2-iodoaniline, 66416-72-6; (*E*)-2-bromo-2′-nitrostilbene, 62640-61-3; *o*-iodonitrobenzene, 609-73-4; *o*-bromostyrene, 2039-88-5.

(5) R. Anschutz, *Chem. Ber.*, **60**, 1322 (1927).
(6) R. Krauss, *Chem. Ber.*, **37**, 223 (1904).
(7) J. Narbutt, *Chem. Ber.*, **52**, 1028 (1919).
(8) W. Miersch, *Chem. Ber.*, **25**, 2109 (1882).