1 H, J = 2.0, 13.7 Hz), 4.67 (X of ABX pattern, 1 H, J = 3.9, 7.8 Hz), 4.85 (dd, 1 H, J = 2.0, 13.7 Hz), 6.76–7.10 (m, 5 H); ^{13}C NMR 26.1 (q), 34.6 (t), 63.2 (d), 63.9 (s), 99.3 (t), 117.2 (d), 120.9 (d), 124.5 (d), 124.9 (d), 128.3 (s), 140.1 (d), 146.5 (s), 167.4 (s), 167.8 ppm (s). Anal. Calcd for $C_{14}H_{13}NO_4$: C, 64.85; H, 5.05; N, 5.40. Found: C, 64.59; H, 5.02; N, 5.34.

Photocycloadduct 8: mp 71.5–72.0 °C; IR (KBr) 2220, 1760, 1495, 1278, 1220, 758 cm^{-1}; ^{1}H NMR δ 0.83 (t, 3 H), 1.1–1.6 (m, 4 H), 1.78 (s, 3 H), 1.7–2.0 (m, 2 H), 2.62 (d, 1 H, J = 12.2 Hz), 3.21 (d, 1 H, J = 12.2 Hz), 6.89–7.26 (m, 4 H); ^{13}C NMR 13.6 (q), 22.4 (t), 25.0 (t), 27.8 (q), 39.3 (t), 42.0 (t), 60.8 (s), 63.8 (s), 117.5 (d), 118.7 (s), 122.9 (d), 125.2 (d), 126.6 (d), 127.6 (s), 146.8 (s), 167.6 ppm (s). Anal. Calcd for $C_{16}H_{18}N_2O_2$: C, 71.08; H, 6.71; N, 10.36. Found: C, 71.05; H, 6.72; N, 10.40.

Photocycloadduct 9: bp 145 °C (2 mmHg); IR (film) 1760, 1740, 1490, 1275, 1200, 1160, 1135, 1125, 750 cm^{-1}; ^{1}H NMR δ 0.85 (t, 3 H), 1.19–1.48 (m, 4 H), 1.72 (s, 3 H), 1.72–2.0 (m, 2 H), 2.35 (d, 1 H, J = 12.2 Hz), 3.18 (d, 1 H, J = 12.2 Hz), 3.42 (s, 3 H), 6.17–6.99 (m, 4 H); ^{13}C NMR 13.6 (q), 22.5 (t), 25.0 (t), 25.6 (q), 40.1 (t), 40.6 (t), 51.6 (q), 63.2 (s), 69.8 (s), 116.7 (d), 120.6 (d), 124.0 (d), 124.5 (d), 129.6 (s), 146.0 (s), 167.6 (s), 171.7 ppm (s). Anal. Calcd for $C_{17}H_{21}NO_4$: C, 67.30; H, 6.92; N, 4.61. Found: C, 67.42; H, 6.94; N, 4.67.

Photocycloadduct 10: bp 135 °C (2 mmHg); IR ($CHCl_3$) 2220, 1750, 1485, 1315, 1270, 1138 cm^{-1}; ^{1}H NMR δ 0.85 (d, 6 H, J = 5.9 Hz), 1.48 (s, 3 H), 0.94–2.02 (m, 5 H), 2.85 (d, 1 H, J = 12.2 Hz), 3.14 (d, 1 H, J = 12.2 Hz), 6.95–7.39 (m, 4 H); ^{13}C NMR 22.3 (2 × q), 27.9 (d), 31.8 (t), 37.7 (t), 42.2 (t), 56.7 (s), 64.0 (s), 117.4 (d), 121.0 (s), 123.1 (d), 125.5 (d), 125.9 (d), 130.3 (s), 146.7 (s), 168.1 ppm (s). Anal. Calcd for $C_{17}H_{20}N_2O_2$: C, 71.80; H, 7.08; N, 9.85. Found: C, 71.77; H, 7.15; N, 9.50.

Photocycloadduct 10′: mp 101–101.5 °C; IR (KBr) 2225, 1762, 1490, 1275, 1140, 1085, 758 cm^{-1}; ^{1}H NMR δ 0.82 (d, 6 H, J = 6.4 Hz), 1.79 (s, 3 H), 1.06–1.97 (m, 5 H), 2.61 (d, 1 H, J = 12.2 Hz), 3.22 (d, 1 H, J = 12.2 Hz), 6.89–7.27 (m, 4 H); ^{13}C NMR 22.3 (2 × q), 27.9 (q), 27.9 (d), 31.6 (t), 37.9 (t), 42.0 (t), 60.8 (s), 63.8 (s), 117.7 (d), 118.7 (s), 123.0 (d), 125.3 (d), 126.6 (d), 127.6 (s), 146.9 (s), 167.7 ppm (s). Anal. Calcd for $C_{17}H_{20}N_2O_2$: C, 71.80; H, 7.08; N, 9.85. Found: C, 71.67; H, 7.09; N, 9.79.

Photocycloadduct 11: bp 135 °C (2 mmHg); IR (film) 1760, 1740, 1485, 1310, 1270, 1200, 1120, 750 cm^{-1}; ^{1}H NMR δ 0.81 (d, 3 H, J = 6.3 Hz), 0.83 (d, 3 H, J = 6.3 Hz), 1.34 (s, 3 H), 1.01–1.97 (m, 5 H), 2.72 (d, 1 H, J = 12.2 Hz), 3.01 (d, 1 H, J = 12.2 Hz), 3.85 (s, 3 H), 6.91–7.41 (m, 4 H); ^{13}C NMR 20.8 (q), 22.3 (2 × q), 28.0 (d), 31.9 (t), 40.6 (t), 52.5 (q), 62.2 (s), 66.8 (s), 116.8 (d), 123.5 (d), 124.5 (d), 124.9 (d), 127.9 (s), 146.6 (s), 169.0 (s), 174.0 ppm (s). Anal. Calcd for $C_{18}H_{23}NO_4$: C, 68.11; H, 7.30; N, 4.41. Found: C, 68.42; H, 7.49; N, 4.49.

Photocycloadduct 11′: bp 130 °C (2 mmHg); IR (film) 1763, 1740, 1495, 1320, 1275, 1205, 1160, 1130, 750 cm^{-1}; ^{1}H NMR δ 0.85 (d, 6 H, J = 5.4 Hz), 1.18–1.56 (m, 3 H), 1.71 (s, 3 H), 1.78–1.97 (m, 2 H), 2.39 (d, 1 H, J = 12.2 Hz), 3.17 (d, 1 H, J = 12.2 Hz), 3.41 (s, 3 H), 6.70–7.00 (m, 4 H); ^{13}C NMR 22.4 (2 × q), 25.8 (q), 28.1 (d), 31.8 (t), 38.9 (t), 40.2 (t), 51.8 (q), 63.4 (s), 69.9 (s), 116.9 (d), 120.8 (d), 124.1 (d), 124.3 (d), 129.7 (s), 146.1 (s), 167.7 (s), 171.8 ppm (s). Anal. Calcd for $C_{18}H_{23}NO_4$: C, 68.11; H, 7.30; N, 4.41. Found: C, 68.33; H, 7.37; N, 4.47.

Reductive dimer *dl*-12a: mp 196–197 °C; IR (KBr) 3390, 1740, 1725, 1615, 1500, 1305, 1225, 1065, 740 cm^{-1}; ^{1}H NMR ($CDCl_3$–Me_2SO-d_6) δ 1.58 (s, 6 H), 6.40 (br s, 2 H), 6.53–6.97 (m, 8 H); ^{13}C NMR ($CDCl_3$–Me_2SO-d_6) 21.9 (2 × q), 63.9 (2 × s), 114.3 (2 × d), 115.4 (2 × d), 117.6 (2 × d), 124.6 (2 × d), 131.1 (2 × s), 139.1 (2 × s), 166.6 ppm (2 × s); (chemical ionization mass spectrum, m/e 325 (QM^+). Anal. Calcd for $C_{18}H_{16}N_2O_4$: C, 66.65; H, 4.97; N, 8.63. Found: C, 66.73; H, 5.00; N, 8.62.

In the ^{1}H NMR spectra of **12a** the methyl protons (δ 1.58) appear at higher field than those (δ 1.66)[11] in *meso*-**12a**, probably due to the shielding effect of the aromatic ring, so we assume that **12a** thus obtained here might be the *dl* isomer.

Reductive dimer *dl*- or *meso*-12b: mp 128.5–129 °C; IR (KBr) 3370, 1730, 1620, 1500, 1305, 1203, 738 cm^{-1}; ^{1}H NMR δ 0.71 (d, 12 H, J = 4.9 Hz), 0.95–1.70 (m, 8 H), 2.10–2.58 (m, 2 H), 5.06 (s, 2 H), 6.63–7.08 (m, 8 H); ^{13}C NMR 22.3 (2 × q), 28.1 (2 × d), 33.1 (2 × t), 34.5 (2 × t), 68.8 (2 × s), 113.6 (2 × d), 116.1 (2 × d), 118.7 (2 × d), 125.8 (2 × d), 131.3 (2 × s), 138.7 (2 × s), 166.8 ppm (2 × s). Anal. Calcd for $C_{26}H_{32}N_2O_4$: C, 71.53; H, 7.38; N, 6.41. Found: C, 71.43; H, 7.39; N, 6.34.

One stereoisomer (*dl*- or *meso*-**12b**) was predominantly formed under these experimental conditions; however, the stereochemistry of **12b** is uncertain at present.

Registry No. **1a**, 7653-60-3; **1b**, 95483-38-8; **1c**, 95483-39-9; **1d**, 27990-57-4; **2a**, 126-98-7; **2b**, 80-62-6; **2c**, 107-13-1; **2d**, 96-33-3; **2e**, 2177-18-6; **3**, 95483-40-2; **3′**, 95483-41-3; **4**, 95483-42-4; **4′**, 95483-43-5; **5**, 95483-44-6; **5′**, 95483-45-7; **6**, 95483-46-8; **6′**, 95483-47-9; **7**, 95483-48-0; **8**, 95483-49-1; **9**, 95483-50-4; **10**, 95483-51-5; **10′**, 95483-52-6; **11**, 95483-53-7; **11′**, 95483-54-8; *dl*-**12a**, 95587-00-1; **12b**, 95483-55-9.

Metallic Nickel-Mediated Synthesis of Ketones by the Reaction of Benzylic, Allylic, Vinylic, and Pentafluorophenyl Halides with Acid Halides

Shin-ichi Inaba and Reuben D. Rieke*

Department of Chemistry, University of Nebraska—Lincoln, Lincoln, Nebraska 68588-0304

Received July 3, 1984

Metallic nickel was investigated as a convenient coupling reagent for the synthesis of ketones by the reaction of benzylic, allylic, vinylic, and pentafluorophenyl halides with acid halides at 85 °C in glyme. A variety of benzylic ketones with functional groups including halogen, cyano, methoxycarbonyl, and hydroxycarbonyl groups were prepared in good yields by this method. The reaction was demonstrated to proceed via organonickel halide intermediates formed by the smooth oxidative addition of benzylic and acyl halides to metallic nickel, which were trapped with electron-deficient olefins. (π-Allyl)nickel halides, prepared in situ at 85 °C from allylic halides and the nickel, also worked for the preparation of ketones. Vinylic and pentafluorophenyl halides but not alkyl halides reacted with acid halides to give the corresponding ketones in moderate yields.

The reaction of organometallic reagents with acid halides is one of the more useful methods for the synthesis of ketones. A variety of organometallic reagents has been employed for this purpose, each of which displays varying degrees of success in avoiding the side reaction of further reaction of the reagents with the ketones formed. For example, organomagnesium,[1,2] -zinc,[1,3] -cadmium,[1] -mercury,[4] -boron,[5] -aluminum,[6,7] -silicon,[8] -copper,[9-11] -zirconium,[12] -manganese,[13] and -rhodium[14] compounds have all

(1) Shirley, D. A. *Org. React. (N.Y.)* **1954**, *8*, 28.

(2) At low temperature: Sato, F.; Inoue, M.; Ogura, K.; Sato, M. *Tetrahedron Lett.* **1979**, 4303. Eberle, M. K.; Kahle, G. G. *Tetrahedron Lett.* **1980**, *21*, 2303. In HMPA: Fauvarque, J.; Ducom, J.; Fauvarque, J. F. *C. R. Hebd. Seances Acad. Sci., Ser. C* **1972**, *275*, 511. In the presence of a catalytic amount of transition-metal halide, for example: Cook, N. C.; Percival, W. C. *J. Am. Chem. Soc.* **1949**, *71*, 4141. Cason, J.; Kraus, K. W. *J. Org. Chem.* **1961**, *26*, 1772.

0022-3263/85/1950-1373$01.50/0

Table I. Yields of 1,2-Diphenyl-1-ethanone (1) Prepared under Various Conditions

benzyl halide	benzoyl halide	NiX_2[a]	molar ratio of $PhCH_2X/PhCOX/Ni$	conditns[b]	yield[c]
$C_6H_5CH_2Cl$	C_6H_5COCl	$NiCl_2$	0.8/0.8/1.0	85 °C, 15 min	11
$C_6H_5CH_2Cl$	C_6H_5COCl	$NiBr_2$	0.8/0.8/1.0	85 °C, 15 min	42
$C_6H_5CH_2Cl$	C_6H_5COCl	NiI_2	0.8/0/8/1.0	rt, 12 h[d]	54
$C_6H_5CH_2Cl$	C_6H_5COCl	NiI_2	0.8/0.8/1.0	50 °C, 3 h	61
$C_6H_5CH_2Cl$	C_6H_5COCl	NiI_2	0.8/0.8/1.0	85 °C, 15 min	73
$C_6H_5CH_2Cl$	C_6H_5COCl	NiI_2	1.0/0.5/1.0	85 °C, 15 min	64
$C_6H_5CH_2Cl$	C_6H_5COCl	NiI_2	0.5/1.0/1.0	85 °C, 15 min	75
$C_6H_5CH_2Br$	C_6H_5COCl	NiI_2	0.8/0.8/1.0	85 °C, 15 min	76
$C_6H_5CH_2Cl$	C_6H_5COBr	NiI_2	0.8/0.8/1.0	85 °C, 15 min	73

[a] Nickel halide used for the preparation of metallic nickel. [b] The reaction was carried out by adding glyme solution (10 mL) of benzyl halide and benzoyl halide to metallic nickel (9–13 mmol) in glyme (25–30 mL) at prescribed temperatures for 30 min, and the mixture was stirred at the same temperature for the prescribed time. [c] Isolated yield by silica gel chromatography. [d] rt = room temperature.

been used for ketone synthesis.[15]

Recently, ketone synthesis involving acid halides and palladium–phosphine complexes in conjunction with organozinc,[16,17] -tin,[18,19] and -mercury[20] compounds has been reported. Bis(1,5-cyclooctadiene)nickel[21,22] and nickel catalyst[23] have also been found to be useful for the ketone synthesis from carboxylates.

In a series of studies on the chemistry of activated metals,[24-39] we have shown that transition metals in the metallic state, prepared by the reduction of the metal halide with an alkali metal in an ethereal solvent, are reactive enough to undergo smooth oxidative addition of organic halides under mild conditions.[26-30,23-34,36-38] For example, the oxidative addition of aromatic,[32,34] benzylic,[32,38] and allylic[27] halides to metallic nickel proceeded readily to give homocoupled products in good yields. The results suggest that nickel in the metallic state could serve as a zerovalent reagent for the preparation of organonickel reagents in situ similar to Grignard reagents.

In general, transition metals in the metallic state have not been acceptable reagents, except for a few examples,[40-42] because their low reactivity with respect to oxidative addition of organic halides. Transition-metal complexes[43] and metal atoms[44] prepared by metal vaporization techniques have been used to overcome this problem. However, our results suggest that organonickel reagents prepared from metallic nickel and organic halides may work as a transition-metal analogue of the Grignard reaction.

In the previous communication, we reported preliminary results on the preparation of benzyl ketones applying the easy oxidative addition of benzyl halides and acid halides to metallic nickel.[36] We present here a full account of our research on the reaction of benzylic, allylic, vinylic, and pentafluorophenyl halides with acid halides in the presence of metallic nickel.

Results and Discussion

Metallic nickel was prepared in 1,2-dimethoxyethane (glyme) by the reduction of nickel halides (1 equiv) with lithium (2.3 equiv) in the presence of a catalytic amount of naphthalene (0.1 equiv) as an electron carrier (eq 1).

(3) Rathke, M. W. *Org. React.* (*N.Y.*) **1975**, *22*, 423.
(4) Larock, R. C.; Bernhardt, J. C. *J. Org. Chem.* **1978**, *43*, 710.
(5) Negishi, E.; Chiu, K.-W.; Yosida, T. *J. Org. Chem.* **1975**, *40*, 1676.
(6) Mole, T.; Jeffrey, E. A. "Organoaluminum Compounds"; Elsevier: Amsterdam, 1972.
(7) Tolstikov, G. A.; Valitov, F. Kh.; Kuchin, A. V. *Zh. Obshch. Khim.* **1982**, *52*, 1328.
(8) Chan, T. H.; Fleming, I. *Synthesis* **1979**, 761.
(9) Posner, G. H. *Org. React.* (*N.Y.*) **1975**, *22*, 253.
(10) Bergbreiter, D. E.; Killough, J. M. *J. Org. Chem.* **1976**, *41*, 2750.
(11) Takai, K.; Oshima, K.; Nozaki, H. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 1281.
(12) Hart, D. W.; Schwartz, J. *J. Am. Chem. Soc.* **1974**, *96*, 8115.
(13) Cahiez, G.; Bernard, D.; Normant, J. F. *Synthesis* **1977**, 130.
(14) Hegedus, L. S.; Kendall, P. M.; Lo, S. M.; Sheats, J. R. *J. Am. Chem. Soc.* **1975**, *97*, 5448.
(15) Tetracarbonylferrate anion has also been used in ketone synthesis: Sawa, Y.; Ryang, M.; Tsutsumi, S. *J. Org. Chem.* **1970**, *35*, 4183. Collman, J. P.; Winter, S. R.; Clark, D. R. *J. Am. Chem. Soc.* **1972**, *94*, 1788.
(16) Sato, T.; Naruse, K.; Enokiya, M.; Fujisawa, T. *Chem. Lett.* **1981**, 1135.
(17) Sato, T.; Itoh, T.; Fujisawa, T. *Chem. Lett.* **1982**, 1559.
(18) Kosugi, M.; Shimizu, Y.; Migita, T. *Chem. Lett.* **1977**, 1423.
(19) Milstein, D.; Stille, J. K. *J. Org. Chem.* **1979**, *44*, 1613.
(20) Takagi, K.; Okamoto, T.; Sakakibara, Y.; Ohno, A.; Oka, S.; Hayama, N. *Chem. Lett.* **1975**, 951.
(21) Onaka, M.; Goto, T.; Mukaiyama, T. *Chem. Lett.* **1979**, 1483.
(22) Goto, T.; Onaka, M.; Mukaiyama, T. *Chem. Lett.* **1980**, 51.
(23) Onaka, M.; Matsuoka, Y.; Mukaiyama, T. *Chem. Lett.* **1981**, 531.
(24) Rieke, R. D. *Top. Curr. Chem.* **1975**, *59*, 1.
(25) Rieke, R. D. *Acc. Chem. Res.* **1977**, *10*, 301.
(26) Rieke, R. D.; Wolf, W. J.; Kujundzic, N.; Kavaliunas, A. V. *J. Am. Chem. Soc.* **1977**, *99*, 4159.
(27) Rieke, R. D.; Kavaliunas, A. V.; Rhyne, L. D.; Fraser, D. J. J. *J. Am. Chem. Soc.* **1979**, *101*, 246.
(28) Rieke, R. D.; Kavaliunas, A. V. *J. Org. Chem.* **1979**, *44*, 3069.
(29) Rieke, R. D.; Rhyne, L. D. *J. Org. Chem.* **1979**, *44*, 3445.
(30) Kavaliunas, A. V.; Rieke, R. D. *J. Am. Chem. Soc.* **1980**, *102*, 5944.
(31) Rieke, R. D.; Li, P. T.-J.; Burns, T. P.; Uhm, S. T. *J. Org. Chem.* **1981**, *46*, 4323.
(32) Inaba, S.; Matsumoto, H.; Rieke, R. D. *Tetrahedron Lett.* **1982**, *23*, 4215.
(33) Kavaliunas, A. V.; Taylor, A.; Rieke, R. D. *Organometallics* **1983**, *2*, 377.
(34) Matsumoto, H.; Inaba, S.; Rieke, R. D. *J. Org. Chem.* **1983**, *48*, 840.
(35) Burns, T. P.; Rieke, R. D. *J. Org. Chem.* **1983**, *48*, 4141.
(36) Inaba, S.; Rieke, R. D. *Tetrahedron Lett.* **1983**, *24*, 2451.
(37) Inaba, S.; Rieke, R. D. *Chem. Lett.* **1984**, 25.
(38) Inaba, S.; Rieke, R. D. *J. Org. Chem.*, in press.
(39) Rochfort, G. L.; Rieke, R. D. *Inorg. Chem.* **1984**, *23*, 787.
(40) Metallic copper has been employed in the Ullmann synthesis of biaryls; however, drastic conditions in the range of 150–280 °C are required: Fanta, P. E. *Synthesis* **1974**, 9. Goshaef, M.; Ostroshchenko, O. S.; Sadykov, A. S. *Russ. Chem. Rev.* (*Engl. Transl.*) **1972**, *41*, 1046.
(41) Iron: Ogata, Y.; Oda, R. *Rikagaku Kenkyusho Iho* (*Tokyo*) **1942**, *21*, 616; *Chem. Abstr.* **1949**, *43*, 2194. Buu-Hoi, Ng. Ph.; Hoan, Ng. *J. Org. Chem.* **1949**, *14*, 1023. Nozaki, H.; Noyori, R. *Tetrahedron* **1966**, *22*, 2163 and references cited therein.
(42) Palladium: Fischer, E. O.; Burger, G. *Z. Naturforsch., B: Anorg. Chem., Org. Chem., Biochem., Biophys., Biol.* **1961**, *16B*, 702. Cobalt and nickel: Agnes, G.; Chiusoli, G. P.; Marraccini, A. *J. Organomet. Chem.* **1973**, *49*, 239.
(43) Tsuji, J. "Organic Synthesis by Means of Transition Metal Complexes"; Springer-Verlag: Berlin/Heidelberg/New York, 1975.
(44) Klabunde, K. J. "Chemistry of Free Atoms and Particles"; Academic Press: New York, 1980.

$$NiX_2 \xrightarrow[\text{glyme}]{\text{Li (2.3 equiv)/}C_{10}H_8\text{ (0.1 equiv)}} Ni \quad (1)$$

After these reagents were stirred for 12 h, the lithium metal was completely consumed and the finely divided metallic nickel appeared as a black powder which settled in a clear colorless solution. The following coupling reactions were carried out by adding dropwise a mixture of the organic halides in glyme to the nickel formed in glyme.

Coupling Reaction of Benzylic Halides with Acid Halides. The reaction of benzylic halides with metallic nickel has been previously shown to proceed at room temperature giving homocoupled products, 1,2-diarylethanes, predominantly and reduction products.[32,38] In contrast, benzyl ketones were found to be formed by adding a mixture of benzylic halides and acid halides to nickel in refluxing glyme (85 °C). The preparation of 1,2-diphenyl-1-ethanone (1) by the reaction of benzyl halide with benzoyl halide was carried out under various conditions (eq 2), and the results are summarized in Table I.

$$PhCH_2X + PhCOX + Ni \xrightarrow[\text{glyme}]{} \underset{\mathbf{1}}{PhCH_2COPh} + NiX_2 \quad (2)$$

The choice of nickel halide used for the preparation of metallic nickel was important. The yields of ketone 1 by the reaction of benzyl chloride with benzoyl chloride at 85 °C were 11% and 42% by using nickel prepared from nickel chloride and bromide, respectively. Nickel iodide was the best source of highly reactive nickel for this coupling reaction, and ketone 1 was obtained in 73% yield. In this case, bibenzyl formed by the homocoupling reaction of benzyl chloride was only 14%. The reaction also proceeded at room temperature or at 50 °C; however, the yields were 54% and 61%, respectively, in favor of homocoupling reaction. A twofold excess use of benzoyl chloride or the use of benzoyl bromide only slightly improved the yields.

A variety of benzylic ketones (**2–28**) were prepared by using benzylic halides, acid chlorides, and metallic nickel prepared from nickel iodide in the molar ratio of 0.8/0.8/1.0 at 85 °C (eq 3); the results are summarized in Table II.

$$ArCH_2X + RCOCl \xrightarrow[\text{glyme, 85 °C}]{\text{metallic Ni}} \underset{\mathbf{2-28}}{ArCH_2COR} \quad (3)$$

Substituents on the benzyl halides and acid chlorides such as chloro, bromo, cyano, methoxycarbonyl, and hydroxycarbonyl groups were compatible with the reaction conditions employed. However, 4-nitrobenzyl chloride failed to couple with acid halides and gave a complex mixture due to the reduction of nitro group by the metallic nickel at 85 °C. The trans configuration of cinnamoyl chloride was retained during its coupling with benzyl chloride. The coupling reaction of benzyl chloride with acryloyl chloride, methacryloyl chloride, or itaconyl chloride failed to give the corresponding α,β-unsaturated ketones, which probably can be explained by the easy oligomerization of these compounds in the presence of the highly reactive nickel at 85 °C.

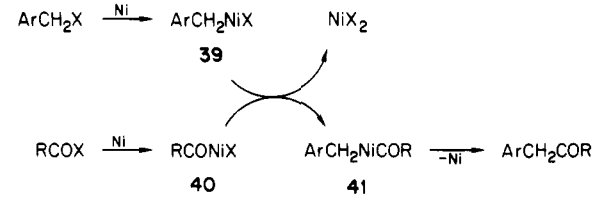
Decarbonylation of acid chlorides was observed in some cases (eq 4). For example, the reaction of benzyl chloride

$$ArCH_2X + RCOCl \xrightarrow[\text{glyme, 85 °C}]{\text{metallic Ni}} ArCH_2COR + ArCH_2COCH_2Ar \quad (4)$$

$$R = CH_3OCH_2,\ C_6H_5CO,\ \text{or}\ (CH_3)_2N$$

with methoxyacetyl chloride afforded 1,3-diphenyl-2-propanone (**30**) in 44% yield along with the expected 1-methoxy-3-phenyl-2-propanone (**29**, 27%). The formation of symmetrical 1,3-diaryl-2-propanone was also observed in the case of benzoylformic acid chloride and dimethylcarbamoyl chloride. Furthermore, pentafluorobenzoyl chloride gave (pentafluorophenyl)phenylmethane (**33**) exclusively instead of the expected benzyl ketone. The reaction with oxalyl chloride gave 1,3-diaryl-2-propanones predominating together with 1,2-diarylethanes.

Scheme I



We have already shown that the homocoupling reaction of aromatic halides mediated by metallic nickel proceed via the arylnickel halide (ArNiX) followed by bis(aryl)nickel (Ar_2Ni) intermediates, which were isolated as their phosphine complexes (Ar = C_6F_5).[32,34] We have also suggested that benzylic halides give the corresponding homocoupled products via oxidative addition to nickel, metathesis of the adducts, and their reductive elimination processes. Actually, the intermediate benzylnickel halide was trapped with electron-deficient olefins such as methyl acrylate and acrylonitrile.[38]

On the other hand, the oxidative addition of acyl halides to zerovalent nickel complexes is known to give the corresponding acylnickel halide complexes.[45] The benzoylnickel chloride intermediate, which was generated in situ by the reaction of benzoyl chloride with bis(1,5-cyclooctadiene)nickel in the presence of triphenylphosphine, was trapped with methyl acrylate.[46] We attempted a trapping experiment of the acylnickel halide intermediate using electron-deficient olefins such as acrylonitrile and 3-buten-2-one. The addition reaction of benzyl chloride to acrylonitrile at 85 °C in the presence of metallic nickel gave 4-oxo-4-phenylbutanenitrile (**37**) in 18% yield. 1-Phenyl-1,4-pentanedione (**38**) was also obtained in 14% yield when 3-buten-2-one was used as the substrate (eq 5).

$$C_6H_5COCl + Ni \xrightarrow[\text{glyme}]{85\text{ °C}} [C_6H_5CONiCl] \xrightarrow{H_2C{=}CHY} [C_6H_5COCH_2C(NiCl)HY] \xrightarrow{H^+} \underset{\substack{\mathbf{37},\ Y = CN\ (18\%)\\ \mathbf{38},\ Y = COCH_3\ (14\%)}}{C_6H_5COCH_2CH_2Y} \quad (5)$$

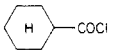
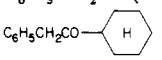
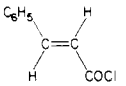
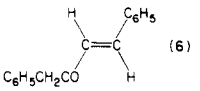
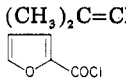
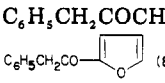
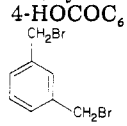
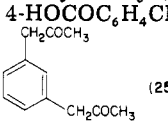
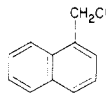
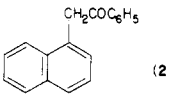
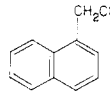
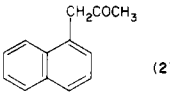
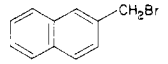
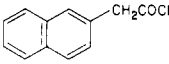
These facts and the previously reported results that the benzyl- and acylnickel halides added to electron-deficient olefins strongly suggest the formation of benzyl- and acylnickel halides as key intermediates in this synthesis.

Thus, the first step of the present reaction may be reasonably explained by the smooth oxidative addition of benzyl halide and acyl halide to nickel to give benzylnickel halide (**39**) and acylnickel halide (**40**), respectively. The metathesis of these complexes could afford an acylbenzylnickel complex (**41**), which upon reductive elimination would yield the benzyl ketone as the final product (Scheme I).

The formation of symmetrical 1,3-diaryl-2-propanones likely arises via decarbonylation of the acylnickel halide (**40**), which was observed in the reaction of benzoyl chloride

(45) Fahey, D. R.; Mahan, J. E. *J. Am. Chem. Soc.* **1977**, *99*, 2501.
(46) Chiusoli, G. P.; Costa, M.; Pecchini, G. *Transition Met. Chem. (Weinheim, Ger.)* **1977**, *2*, 270.

Table II. Reaction of Benzylic Halides with Acid Chlorides Mediated by Metallic Nickel[a]

benzylic halide	acid halide	product	yield,[b] %
$C_6H_5CH_2Cl$	C_6H_5COCl	$C_6H_5CH_2COC_6H_5$ (1)	73
$C_6H_5CH_2Cl$	4-ClC_6H_4COCl	$C_6H_5CH_2COC_6H_4Cl$-4 (2)	72
$C_6H_5CH_2Cl$	CH_3COCl	$C_6H_5CH_2COCH_3$ (3)	68
$C_6H_5CH_2Cl$	$CH_3(CH_2)_6COCl$	$C_6H_5CH_2CO(CH_2)_6CH_3$ (4)	83
$C_6H_5CH_2Cl$		 (5)	55
$C_6H_5CH_2Cl$		 (6)	64
$C_6H_5CH_2Cl$	$(CH_3)_2C{=}CHCOCl$	$C_6H_5CH_2COCH{=}C(CH_3)_2$ (7)	70
$C_6H_5CH_2Br$		 (8)	39
$C_6H_5CH_2Br$	$CH_3OCOCH_2CH_2COCl$	$C_6H_5CH_2COCH_2CH_2CO_2CH_3$ (9)	55
$C_6H_5CH_2Cl$	$CH_3OCOCH_2CH_2CH_2COCl$	$C_6H_5CH_2COCH_2CH_2CH_2CO_2CH_3$ (10)	73
$C_6H_5CH_2Cl$	$ClCOCH_2CH_2COCl$	$C_6H_5CH_2COCH_2CH_2COCH_2C_6H_5$ (11)	25
$C_6H_5CH_2Br$	$ClCOCH_2CH_2COCl$	11	30
$C_6H_5CH(CH_3)Cl$	C_6H_5COCl	$C_6H_5CH(CH_3)COC_6H_5$ (12)	71
4-$CH_3C_6H_4CH_2Cl$	C_6H_5COCl	4-$CH_3C_6H_4CH_2COC_6H_5$ (13)	71
3-$CF_3C_6H_4CH_2Cl$	C_6H_5COCl	3-$CF_3C_6H_4CH_2COC_6H_5$ (14)	66
3-$CH_3OC_6H_4CH_2Cl$	C_6H_5COCl	3-$CH_3OC_6H_4CH_2COC_6H_5$ (15)	65
4-$FC_6H_4CH_2Cl$	C_6H_5COCl	4-$FC_6H_4CH_2COC_6H_5$ (16)	69
4-$ClC_6H_4CH_2Cl$	C_6H_5COCl	4-$ClC_6H_4CH_2COC_6H_5$ (17)	82
2-$BrC_6H_4CH_2Br$	C_6H_5COCl	2-$BrC_6H_4CH_2COC_6H_5$ (18)	79
4-$BrC_6H_4CH_2Br$	C_6H_5COCl	4-$BrC_6H_4CH_2COC_6H_5$ (19)	57
4-$BrC_6H_4CH_2Br$	CH_3COCl	4-$BrC_6H_4CH_2COCH_3$ (20)	78
2-$NCC_6H_4CH_2Br$	CH_3COCl	2-$NCC_6H_4CH_2COCH_3$ (21)	83
4-$NCC_6H_4CH_2Br$	CH_3COCl	4-$NCC_6H_4CH_2COCH_3$ (22)	85
4-$CH_3OCOC_6H_4CH_2Cl$	C_6H_5COCl	4-$CH_3OCOC_6H_4CH_2COC_6H_5$ (23)	71
4-$HOCOC_6H_4CH_2Br$	CH_3COCl	4-$HOCOC_6H_4CH_2COCH_3$ (24)	44
	CH_3COCl	 (25)	62
	C_6H_5COCl	 (26)	73
	CH_3COCl	 (27)	79
	CH_3COCl	 (28)	62
$C_6H_5CH_2Cl$	CH_3OCH_2COCl	$C_6H_5CH_2COCH_2OCH_3$ (29)	27
		$C_6H_5CH_2COCH_2C_6H_5$ (30)	44[c]
4-$CH_3C_6H_4CH_2Cl$	$C_6H_5COCOCl$	4-$CH_3C_6H_4CH_2COC_6H_5$ (13)	41
		4-$CH_3C_6H_4CH_2COCH_2C_6H_4CH_3$-4 (31)	24[c]
$C_6H_5CH_2Cl$	$(CH_3)_2NCOCl$	$C_6H_5CH_2CON(CH_3)_2$ (32)	44
		30	8[c]
$C_6H_5CH_2Cl$	C_6F_5COCl	$C_6H_5CH_2C_6F_5$ (33)[d]	51
$C_6H_5CH_2Cl$ (2 equiv)	$ClCOCOCl$ (1 equiv)[e]	30[f]	52[c]
$C_6H_5CH_2Cl$ (1 equiv)	$ClCOCOCl$ (1 equiv)[g]	30[h]	60[c]
4-$CH_3OCOC_6H_4CH_2Cl$	$ClCOCOCl$[g]	4-$CH_3OCOC_6H_4CH_2COCH_2C_6H_4CO_2CH_3$ (34)	59[c]
2-$NCC_6H_4CH_2Br$	$ClCOCOCl$[g]	2-$NCC_6H_4CH_2COCH_2C_6H_4CN$-2 (35)	55[c]
4-$NCC_6H_4CH_2Br$	$ClCOCOCl$[g]	4-$NCC_6H_4CH_2COCH_2C_6H_4CN$-4 (36)	56[c]

[a] The reaction was carried out at 85 °C using the reagents in the molar ratio of benzylic halide/acid halide/metallic nickel = 0.8/0.8/1.0 unless otherwise noted. [b] Isolated yield by silica gel chromatography. [c] Isolated yield based on benzyl halide used. [d] 1-(Pentafluorophenyl)-2-phenyl-1-ethanone could not be detected. [e] Benzyl chloride/oxalyl chloride/metallic nickel = 0.8/0.4/1.0. [f] 1,2-Diphenylethane was also isolated in 33% yield. [g] Benzyl chloride/oxalyl chloride/metallic nickel = 0.5/0.5/1.0. [h] 1,2-Diphenylethane was also isolated in 15% yield.

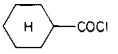
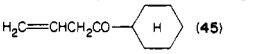
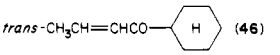
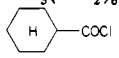
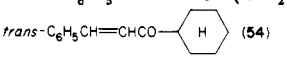
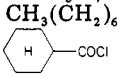
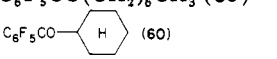
with tetrakis(triphenylphosphine)nickel.[47] The insertion of carbon monoxide formed from **40** into the benzyl–nickel bond of benzylnickel halide (**39**) would afford the (arylacetyl)nickel halide (**42**). The metathesis of the complexes **39** and **42** seems to give 1,3-diaryl-2-propanone as the final product (Scheme II).

In the case of the reaction with oxalyl chloride, a similar decarbonylation of the nickel complex formed and carbonylation of **39** may proceed smoothly to give symmetrical 1,3-diaryl-2-propanone via (arylacetyl)nickel complex (**42**). Symmetrical 1,3-diaryl-2-propanones have been prepared from benzyl halides by the reaction with nickel[48] and iron[49–51] carbonyls, disodium tetracarbonylferrate,[52] or

(47) Otsuka, S.; Nakamura, A.; Yoshida, T.; Naruto, M.; Ataka, K. *J. Am. Chem. Soc.* **1972**, *95*, 3180.

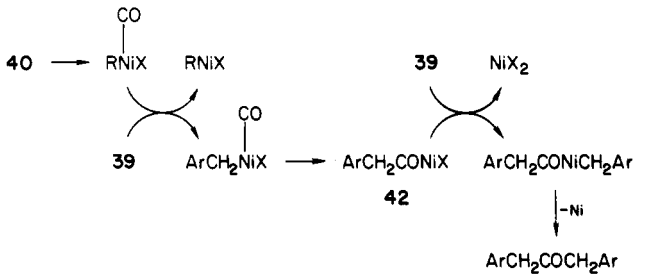
(48) Yoshisato, E.; Tsutsumi, S. *J. Org. Chem.* **1968**, *33*, 869.

Table III. Reaction of Allylic, Vinylic, and Pentafluorophenyl Halides with Acid Halides Mediated by Metallic Nickel[a]

organic halide	acid halide	product	yield,[b] %
$H_2C{=}CHCH_2Br$	C_6H_5COCl	$H_2C{=}CHCH_2COC_6H_5$ (43)	36[c]
		trans-$CH_3CH{=}CHCOC_6H_5$ (44)	13[c]
$H_2C{=}CHCH_2Br$		 (45)	37
		 (46)	9
$H_2C{=}C(CH_3)CH_2Cl$	C_6H_5COCl	$H_2C{=}C(CH_3)CH_2COC_6H_5$ (47)	39[c]
		$(CH_3)_2C{=}CHCOC_6H_5$ (48)	5[c]
trans-$C_6H_5CH{=}CHCH_2Br$	C_6H_5COCl	*trans*-$C_6H_5CH{=}CHCH_2COC_6H_5$ (49)	39
trans-$C_6H_5CH{=}CHCH_2Br$	$CH_3(CH_2)_6COCl$	*trans*-$C_6H_5CH{=}CHCH_2CO(CH_2)_6CH_3$ (50)	76
trans-$C_6H_5CH{=}CHCH_2Br$	$CH_3OCO(CH_2)_3COCl$	*trans*-$C_6H_5CH{=}CHCH_2CO(CH_2)_3CO_2CH_3$ (51)	51
$CH_3CH{=}CHBr$[d]	C_6H_5COCl	44	17
trans-$C_6H_5CH{=}CHBr$	CH_3COCl	*trans*-$C_6H_5CH{=}CHCOCH_3$ (52)	30
trans-$C_6H_5CH{=}CHBr$	$CH_3(CH_2)_6COCl$	*trans*-$C_6H_5CH{=}CHCO(CH_2)_6CH_3$ (53)	44
trans-$C_6H_5CH{=}CHBr$		 (54)	45
trans-$C_6H_5CH{=}CHBr$	$(CH_3)_2C{=}CHCOCl$	*trans*-$C_6H_5CH{=}CHCOCH{=}C(CH_3)_2$ (55)	25
trans-$C_6H_5CH{=}CHBr$	$CHH_3OCO(CH_2)_3COCl$	*trans*-$C_6H_5CH{=}CHCO(CH_2)_3CO_2CH_3$ (56)	35
C_6F_5I	C_6H_5COCl	$C_6F_5COC_6H_5$ (57)	54
C_6F_5I	4-ClC_6H_4COCl	$C_6F_5COC_6H_4Cl$-4 (58)	60
C_6F_5I	$CH_3(CH_2)_6COCl$	$C_6F_5CO(CH_2)_6CH_3$ (59)	53
C_6F_5I		 (60)	38
C_6F_5I	$CH_3OCO(CH_2)_3COCl$	$C_6F_5CO(CH_2)_3CO_2CH_3$ (61)	29

[a] The reaction was carried out at 85 °C using the reagents in the molar ratio of organic halide/acid halide/metallic nickel = 0.8/0.8/1.0. [b] Isolated yield by silica gel chromatography unless otherwise noted. [c] Yield was calculated from the NMR ratio of ketone isomers purified. [d] A mixture of isomers (bp 58–63 °C) was used.

Scheme II



potassium hexacyanodinickelate–carbon monoxide.[53] In contrast for this reaction, oxalyl chloride worked well as a source of carbon monoxide for the ketone synthesis and could be used instead of free or coordinated carbon monoxide.

A related reaction using alkyl oxalyl chlorides also proceeded to give 1,3-diaryl-2-propanones in moderate yields, which was reported previously[37] (eq 6).

$$2ArCH_2X + ClCOCO_2R \xrightarrow[85\ °C,\ glyme]{metallic\ Ni} ArCH_2COCH_2Ar + {}^1/_2ROCOCOOR \quad (6)$$

Reaction of Allylic, Vinylic, and Pentafluorophenyl Halides with Acid Halides Mediated by Metallic Nickel. The use of allylic, vinylic, and pentafluorophenyl halides also proved to be useful in the synthesis of ketones. The results of these studies are summarized in Table III.

3-Bromo-1-propene and benzoyl chloride or cyclohexanecarbonyl chloride reacted with the metallic nickel at 85 °C to give a mixture of 1-substituted 3-buten-1-ene and 2-buten-1-one in moderate yields. 3-Chloro-2-methyl-1-propene afforded a mixture of the corresponding α,β- and β,γ-unsaturated ketones. These β,γ-unsaturated ketones seem to be relatively unstable under the reaction conditions employed and the prolonged reaction time resulting in the isomerization of β,γ-unsaturated ketones to their isomers. A similar isomerization was reported in the reaction of the (π-allyl)nickel bromide with benzoyl chloride[54] or 2-pyridyl carboxylates.[21] The intermediate of the present reaction is presumably the (π-allyl)nickel halide, which would have been formed by the oxidative addition of allylic halides to the metallic nickel.[55]

Although (π-allyl)nickel halides have been widely used as mild and selective reagents for the carbon–carbon bond formation,[56] they have demonstrated poor reactivity toward acid halides at room temperature.[57,58] (π-Allyl)nickel halides prepared from allyl halides and nickel carbonyl or bis(1,5-cyclooctadiene)nickel have a limitation that the reaction temperature cannot be raised above 70 °C in polar solvents due to their rapid thermal decomposition.[59] This problem can be overcome with the use of (π-allyl)nickel halides prepared in situ from metallic nickel.

On the other hand, the reaction of *trans*-3-bromo-1-phenyl-1-propene with acid halides gave the corresponding trans-β,γ-unsaturated ketones exclusively. *trans*-β-Bromostyrene reacted with the acid halides with retention of its configuration and afforded *trans*-α,β-unsaturated ketones in moderate yields. Iodopentafluorobenzene was reactive enough to couple with acid chlorides in contrast

(49) Nesmeyanov, A. N.; Zol'nikova, G. P.; Babakhina, G. M.; Kritskaya, I. I.; Yakobson, G. G. *Zh. Obshch. Khim.* **1973**, *43*, 2007.
(50) Rhee, I.; Ryang, M.; Tsutsumi, S. *J. Organomet. Chem.* **1967**, *9*, 361.
(51) Rhee, I.; Mizuta, N.; Ryang, M.; Tsutsumi, S. *Bull. Chem. Soc. Jpn.* **1968**, *41*, 1417.
(52) Kimura, Y.; Tomita, Y.; Nakanishi, S.; Otsuji, Y. *Chem. Lett.* **1979**, 321.
(53) Hashimoto, I.; Tsuruta, N.; Ryang, M.; Tsutsumi, S. *J. Org. Chem.* **1970**, *35*, 3748.
(54) The yield of ketones formed was low (11%); see ref 21.
(55) Discussed in ref 27.
(56) Semmelhack, M. F. *Org. React. (N.Y.)* **1972**, *19*, 115.
(57) Hegedus, L. S.; Wagner, S. D.; Waterman, E. L.; Siirala-Hansen, K. *J. Org. Chem.* **1975**, *40*, 593.
(58) Page 162 in ref 56.
(59) Ottenheijm, H. C. J.; de Man, J. H. M. *Synthesis* **1975**, 163.

to general aromatic halides and pentafluorophenyl ketones were prepared by the present method in modest yields.

We were unable to effectively couple alkyl halides with acid chlorides. This appears to be due to the reduced reactivity of alkyl halides toward the metallic nickel. For example, 1-iodoheptane was found to be unreactive toward the metallic nickel and was recovered in high yield.

In conclusion, a variety of benzylic, allylic, vinylic, and pentafluorophenyl ketones were prepared by the present method under relatively mild conditions. Substituents including halogen, cyano, methoxycarabonyl, and hydroxycarbonyl groups were compatible with the reaction conditions employed. Prepared and handling of the metallic nickel is quite easy and no special apparatus is required. The following coupling reactions could be completed within 1 h at 85 °C. A simple procedure, short reaction time, and reaction conditions of glyme are useful advantages in this method.

Experimental Section

Melting points and boiling points are uncorrected. The infrared spectra were taken on a Perkin-Elmer 283 spectrophotometer using samples as a KBr disk or a neat liquid. The nuclear magnetic resonance spectra were obtained on a Varian EM 390 spectrometer with Me_4Si as the internal standard. Mass spectra were recorded on a Kratos MS-80 spectrometer. Analytical gas chromatography was carried out on a Hewlett-Packard 5702A using a column packed with silicon OV-17 (3%) on Chromosorb W.

Benzylic, allylic, vinylic, and pentafluorophenyl halides and acid halides were commercially avvailable and were used as received. Benzoylformic acid chloride was prepared by the reaction of benzoylformic acid and dichloromethoxymethane.[59] Anhydrous nickel halides were purchased from Cerac, Inc., and were used as received. Lithium (rod, 1.27-cm diameter) was obtained from Alfa Products. Morton Thiokol, Inc. 1,2-Dimethoxyethane (glyme) was distilled prior to use from sodium–potassium alloy under argon.

Preparation of metallic nickel and of ketones by the coupling reaction mediated by the nickel was carried out in an atmosphere of argon, and a typical procedure is as follows.

Preparation of Metallic Nickel. A 50-mL two-neck flask was equipped with a magnetic stirrer, a rubber septum, and a condenser topped with argon inlet and outlet to oil pump. Lithium metal was cut under mineral oil. One piece of lithium with a shining metal surface was rinsed in hexane and transferred into a glass tube with a stopcock and a rubber septum which had been filled with argon. The glass tube was evacuated to evaporate the hexane, filled with argon, and weighed. Nickel halide (1.0 equiv, 9–13 mmol), lithium (2.3 equiv, 21–30 mmol), and naphthalene (0.1 equiv, 0.9–1.3 mmol) were placed in the flask through the side neck. The flask was evacuated and filled with argon two or three times. The use of a glovebox or -bag is not required if contact of the lithium with air is kept to a minimum.

Then, glyme (25–30 mL) was added through the septum with a syringe, and the mixture was stirred for 12 h. During the reduction the surface of lithium became pink. After the lithium metal was consumed completely, the stirring was stopped; metallic nickel which had adhered to the walls of the flask was scraped off with the stirrer and a magnet. The nickel precipitated as a bulky black powder in a clear colorless solution after standing.

The septum on the side neck was replaced with an addition funnel, and a mixture of appropriate reagents in glyme (10 mL) was then added to the nickel.

Reaction of Benzyl Chloride with Benzoyl Chloride in the Presence of Metallic Nickel. Metallic nickel in glyme (25 mL), prepared from nickel iodide (2.97 mmol), lithium (0.152 g, 21.9 mmol), and naphthalene (0.122 g, 0.95 mmol), was heated to reflux. A mixture of benzyl chloride (0.196 g, 7.24 mmol) and benzoyl chloride (1.07 g, 7.61 mmol) in glyme (10 mL) was added dropwise for 30 min. Additional heating was continued for 15 min, and the red-brown reaction mixture was cooled to room temperature, poured into a separatory funnel containing hydrochloric acid solution (3%, 100 mL), and extracted with chloroform twice. The chloroform solution was washed with water, and the aqueous phase was extracted with additional chloroform. The combined extracts were dried over anhydrous sodium sulfate and concentrated. The crude oil was purified by silica gel chromatography. It was eluted with hexane followed by chloroform to give 1,2-diphenylethane (0.086 g, 14%) and 1,2-diphenyl-1-ethanone (1, 1.04 g, 73%). 1: mp 55–56 °C (lit.[60] mp 56 °C); IR (KBr) 1680 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.27 (s, CH_2, 2 H), 7.10–7.70 (m, arom, 8 H), 7.90–8.15 (m, arom, 2 H).

1-(4-Chlorophenyl)-2-phenyl-1-ethanone (2): mp 105–105.5 °C (lit.[61] mp 107.5 °C); IR (KBr) 1675 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.30 (s, cH_2, 2 H), 7.28 (s, arom, 5 H), 7.40 (d, J = 9 Hz, arom, 2 H), 7.93 (d, J = 9 Hz, arom, 2 H).

1-Phenyl-2-propanone (3): bp 95–96 °C (11 mmHg) [lit.[62] bp 97–98.5 °C (13 mmHg)]; IR (neat) 1710 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.11 (s, CH_3, 3 H), 3.67 (s, CH_2, 2 H), 7.10–7.50 (m, arom, 5 H).

1-Phenyl-2-nonanone (4): bp 158 °C (11 mmHg) [lit.[63] bp 75–80 °C (0.05 mmHg)]; IR (neat) 1705 cm^{-1} (C=O); NMR ($CDCl_3$) δ 0.87 (t, J = 6 Hz, CH_3, 3 H), 1.05–1.80 (m, CH_2, 10 H), 2.42 (t, J = 7.5 Hz, CH_2CO, 2 H), 3.67 (s, $ArCH_2$, 2 H), 7.10–7.50 (m, arom, 5 H).

1-Cyclohexyl-2-phenyl-1-ethanone (5): bp 102–103 °C (0.6 mmHg) [lit.[64] bp 138–139 °C (5 mmHg)]; IR (neat) 1710 cm^{-1} (C=O); NMR ($CDCl_3$) δ 0.80–2.10 (m, CH_2, 10 H), 2.20–2.65 (m, CH, 1 H), 3.71 (s, CH_2, 2 H), 7.00–7.50 (m, arom, 5 H).

***trans*-1,4-Diphenyl-3-buten-2-one (6)**: mp 72–73 °C (lit.[65] mp 69–73 °C); IR (KBr) 1655 (C=O), 1620 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 3.91 (s, CH_2, 2 H), 6.75 (d, J = 16 Hz, CH, 1 H), 7.20–7.60 (m, arom, 10 H), 7.63 (d, J = 16 Hz, CH, 1 H).

4-Methyl-1-phenyl-3-penten-2-one (7): bp 129 °C (11 mmHg) [lit.[66] bp 137.5–138 °C (14 mmHg)]; IR (neat) 1680 (C=O), 1615 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 1.84 (d, J = 1.3 Hz, CH_3, 3 H), 2.16 (d, J = 1.3 Hz, Ch_3, 3 H), 3.68 (s, CH_2, 2 H), 6.07–6.23 (m, CH, 1 H), 7.10–7.53 (m, arom, 5 H).

1-(2-Furyl)-2-phenyl-1-ethanone (8): bp 104 °C (0.6 mmHg) [lit.[67] bp 161–163 °C (10 mmHg)]; IR (neat) 1670 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.10 (s, CH_2, 2 H), 6.50 (d or d, J = 1 and 3 Hz, CH, 1 H), 7.21 (d, J = 3 Hz, CH, 1 H), 7.32 (s, C_6H_5, 5 H), 7.58 (d, J = 1 Hz, CH, 1 H).

Methyl 4-oxo-5-phenylpentanoate (9): bp 110–111 °C (0.45 mmHg) [lit.[68] bp 150 °C (0.01 mmHg)]; IR (neat) 1735 (C=O), 1720 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 2.42–2.90 (m, CH_2, 4 H), 3.63 (s, OCH_3, 3 H), 3.72 (s, CH_2Ar, 2 H), 7.07–7.50 (m, arom, 5 H); spectral data were consistent with those reported.[68]

Methyl 5-oxo-6-phenylhexanoate (10): bp 106 °C (0.17 mmHg); IR (neat) 1730 (C=O), 1705 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 1.83 (q, J = 7.5 Hz, CH_2, 2 H), 2.27 (t, J = 7.5 Hz, CH_2CO_2, 2 H), 2.50 (t, J = 7.5 Hz, CH_2CO, 2 H), 3.59 (s, OCH_3, 3 H), 3.63 (s, CH_2Ar, 2 H), 7.07–7.47 (m, arom, 5 H). Anal. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.86; H, 7.36.

1,6-Diphenyl-2,5-hexanedione (11): mp 64–64.5 °C (lit.[69] mp 63–64 °C); IR (KBr) 1710 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.67 (s, CH_2, 4 H), 3.71 (s, CH_2Ar, 4 H), 7.07–7.50 (m, arom, 10 H).

1,2-Diphenyl-1-propanone (12): mp 50.5–51 °C; bp 181 °C (17 mmHg) [lit.[70] mp 52 °C; bp 140 °C (1 mmHg)]; IR (neat) 1680 cm^{-1} (C=O); NMR ($CDCl_3$) δ 1.53 (d, J = 7 Hz, CH_3, 3 H), 4.63 (q, J = 7 Hz, CH, 1 H), 7.00–7.53 (m, arom, 8 H), 7.83–8.10 (m, arom, 2 H).

(60) Fischer, A.; Grigor, B. A.; Packer, J.; Vaughan, J. *J. Am. Chem. Soc.* **1961**, *83*, 4208.
(61) Jenkins, S. S.; Richardson, E. M. *J. Am. Chem. Soc.* **1933**, *55*, 1618.
(62) Walker, H. G.; Hauser, C. R. *J. Am. Chem. Soc.* **1946**, *68*, 1386.
(63) Grayson, J. I.; Warren, S. *J. Chem. Soc., Perkin Trans. 1* **1977**, 2263.
(64) Bolshukhin, A. I.; Orlova, A. N. *Zh. Obshch. Khim.* **1957**, *27*, 651.
(65) Southwick, P. L.; Sapper, D. I. *J. Org. Chem.* **1954**, *19*, 1926.
(66) Colonge, J.; Chambion, J. *Bull Soc. Chim. Fr.* **1947**, 1002.
(67) Takagi, S.; Yasuda, H.; Kono, M. *Yakugaku Zasshi* **1961**, *81*, 1559; *Chem. Abstr.* **1962**, *57*, 16582b.
(68) Wegmann, H.; Schulz, G.; Steglich, W. *Liebigs Ann. Chem.* **1980**, 1736.
(69) Sudweeks, W. B.; Broadbent, H. S. *J. Org. Chem.* **1975**, *40*, 1131.
(70) Christol, H.; Laurent, A.; Solladie, G. *Bull. Soc. Chim. Fr.* **1963**, 877.

2-(4-Methylphenyl)-1-phenyl-1-ethanone (13): mp 95–96 °C (lit.[60] mp 95.5 °C); IR (KBr) 1685 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.32 (s, CH_3, 3 H), 4.23 (s, CH_2, 2 H), 7.03–7.70 (m, arom, 7 H), 7.95–8.20 (m, arom, 2 H).

1-Phenyl-2-[3-(trifluoromethyl)phenyl]-1-ethanone (14): mp 35–36 °C, bp 119 °C (0.45 mmHg) [lit.[71] mp 35–37 °C; bp 146–148 °C (2 mmHg)]; IR (KBr) 1670 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.30 (s, CH_2, 2 H), 7.23–7.70 (m, arom, 7 H), 7.80–8.20 (m, arom, 2 H).

2-(3-Methoxyphenyl)-1-phenyl-1-ethanone (15): bp 140–143 °C (0.27 mmHg); IR (neat) 1675 cm^{-1} (C=O); NMR ($CDCl_3$) δ 3.73 (s, CH_3, 3 H), 4.03 (s, CH_2, 2 H), 6.66–6.93 (m, arom, 3 H), 7.09–7.64 (m, arom, 4 H), 7.90–8.13 (m, arom, 2 H); mass spectrum, m/e 226.0994, calcd for $C_{15}H_{14}O_2$ 226.0994.

2-(4-Fluorophenyl)-1-phenyl-1-ethanone (16): mp 110–111 °C (lit.[60] mp 111 °C); IR (KBr) 1675 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.19 (s, CH_2, 2 H), 6.81–7.67 (m, arom, 7 H), 7.87–8.13 (m, arom, 2 H).

2-(4-Chlorophenyl)-1-phenyl-1-ethanone (17): mp 135–136 °C (lit.[60] mp 136.5 °C); IR (KBr) 1675 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.24 (s, CH_2, 2 H), 7.10–7.65 (m, arom, 7 H), 7.93–8.13 (m, arom, 2 H).

2-(2-Bromophenyl)-1-phenyl-1-ethanone (18): mp 67–68 °C (lit.[72] mp 69.5–70 °C); IR (KBr) 1680 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.40 (s, CH_2, 2 H), 6.77–7.67 (m, arom, 7 H), 7.90–8.20 (m, arom, 2 H).

2-(4-Bromophenyl)-1-phenyl-1-ethanone (19): mp 150–151 °C (lit.[73] mp 146–147 °C); IR (KBr) 1680 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.18 (s, CH_2, 2 H), 6.85–7.73 (m, arom, 7 H), 7.88–8.10 (m, arom, 7 H), 7.88–8.10 (m, arom, 2 H).

1-(4-Bromophenyl)-2-propanone (20): bp 139 °C (11 mmHg) [lit.[74] bp 110 °C (0.3 mmHg)]; IR (neat) 1705 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.17 (s, CH_3, 3 H), 3.67 (s, CH_2, 2 H), 7.13 (d, J = 9 Hz, arom, 2 H), 7.50 (d, J = 9 Hz, arom, 2 H).

1-(2-Cyanophenyl)-2-propanone (21): mp 28–29 °C, bp 98 °C (0.34 mmHg); IR (KBr) 2215 (C≡N), 1700 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 2.27 (s, CH_3, 3 H), 3.96 (s, CH_2, 2 H), 7.13–7.73 (m, arom, 4 H). Anal. Calcd for $C_{10}H_9NO$: C, 75.45; H, 5.70; N, 8.80. Found: C, 75.63; H, 5.68; N, 8.91.

1-(4-Cyanophenyl)-2-propanone (22): mp 79–79.5 °C (lit.[75] mp 78–80 °C); IR (KBr) 2220 (C≡N), 1705 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 2.23 (s, CH_3, 3 H), 3.80 (s, CH_2, 2 H), 7.33 (d, J = 7.5 Hz, arom, 2 H), 7.65 (d, J = 7.5 Hz, arom, 2 H).

2-[4-(Methoxycarbonyl)phenyl]-1-phenyl-1-ethanone (23): mp 134–135 °C; IR (KBr) 1710 (C=O), 1675 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 3.84 (s, OCH_3, 3 H), 4.29 (s, CH_2, 2 H), 7.23–7.68 (m, arom, 5 H), 7.87–8.13 (m, arom, 4 H). Anal. Calcd for $C_{16}H_{14}O_3$: C, 75.58; H, 5.55. Found: C, 75.62; H, 5.68.

4-(2-Oxopropyl)benzoic acid (24): mp 156–157 °C; IR (KBr) 3000–2500 (OH), 1710 (C=O), 1675 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 2.20 (s, CH_3, 3 H), 3.79 (s, CH_2, 2 H), 7.33 (d, J = 9 Hz, arom, 2 H), 8.10 (d, J = 9 Hz, arom, 2 H); mass spectrum, m/e 178.0625, calcd for $C_{10}H_{10}O_3$ 178.0650. Anal. Calcd for $C_{10}H_{10}O_3$: C, 67.41; H, 5.66. Found: C, 67.37; H, 5.80.

1,3-Bis(2-oxopropyl)benzene (25): bp 121 °C (0.4 mmHg) [lit.[76] bp 146 °C (3 mmHg)]; IR (neat) 1710 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.17 (s, CH_3, 6 H), 3.71 (s, CH_2, 4 H), 6.95–7.50 (m, arom, 4 H).

1-Phenyl-2-(1-naphthyl)-1-ethanone (26): mp 106.5–107 °C (lit.[77] mp 109–110 °C); IR (KBr) 1675 cm^{-1} (C=O); NMR ($CDCl_3$) δ 4.66 (s, CH_2, 2 H), 7.20–8.17 (m, arom, 12 H).

1-(1-Naphthyl)-2-propanone (27): bp 90–91 °C (0.13 mmHg) [lit.[78] bp 132–134 °C (1 mmHg)]; IR (neat) 1700 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.04 (s, CH_3, 3 H), 4.02 (s, CH_2, 2 H), 7.15–7.60 (m, arom, 4 H), 7.65–8.05 (m, Arom, 4 H).

1-(2-Naphthyl)-2-propanone (28): mp 34–35 °C (lit.[79] mp 36–37.2 °C); IR (KBr) 1710 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.07 (s, CH_3, 3 H), 3.73 (s, CH_2, 2 H), 7.13–7.90 (m, arom, 7 H).

1-Methoxy-3-phenyl-2-propanone (29): bp 118 °C (11 mmHg) [lit.[80] molecular distillation: bath temperature 100 °C (1 mmHg)]; IR (neat) 1720 cm^{-1} (C=O); NMR ($CDCl_3$) δ 3.36 (s, OCH_3, 3 H), 3.73 (s, CH_2Ar, 2 H), 4.01 (s, OCH_2, 2 H), 7.10–7.50 (m, arom, 5 H); mass spectrum, m/e 164.0838, calcd for $C_{10}H_{12}O_2$ 164.0836.

1,3-Diphenyl-2-propanone (30): bp 125–127 °C (0.8 mmHg) [lit.[50] bp 105–110 °C (0.4 mmHg)]; IR (neat) 1705 cm^{-1} (C=O); NMR ($CDCl_3$) δ 3.70 (s, CH_2, 4 H), 7.00–7.47 (m, arom, 10 H).

1,3-Bis(4-methylphenyl)-2-propanone (31): mp 54–55 °C (lit.[53] mp 54–55 °C); IR (KBr) 1700 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.32 (s, CH_3, 6 H), 3.64 (s, CH_2, 4 H), 7.03 (d, J = 9 Hz, arom, 4 H), 7.13 (d, J = 9 Hz, Arom, 4 H).

***N,N*-Dimethyl-2-phenylethanamide (32)**: mp 40–41 °C (lit.[81] mp 43–44 °C); IR (KBr) 1620 cm^{-1} (C=O); NMR ($CDCl_3$) δ 2.96 (s, CH_3, 3 H), 2.98 (s, CH_3, 3 H), 3.70 (s, CH_2, 2 H), 7.28 (s, arom, 5 H).

(Pentafluorophenyl)phenylmethane (33): mp 55–56 °C, bp 122 °C (22 mmHg) (lit.[82] mp 56–57 °C); NMR ($CDCl_3$) δ 3.97 (t, J = 1.9 Hz, CH_2, 2 H), 7.25 (s, arom, 5 H).

1,3-Bis[4-(methoxycarbonyl)phenyl]-2-propanone (34): mp 140–141 °C; IR (KBr) 1720, 1705 cm^{-1} (C=O); NMR ($CDCl_3$) δ 3.77 (s, CH_2, 4 H), 3.89 (s, OCH_3, 6 H), 7.20 (d, J = 9 Hz, arom, 4 H), 7.97 (d, J = 9 Hz, arom, 4 H); mass spectrum, m/e 326.1136, calcd for $C_{19}H_{18}O_5$ 326.1153. Anal. Calcd for $C_{19}H_{18}O_5$: C, 69.93; H, 5.56. Found: C, 69.75; H, 5.65.

1,3-Bis(2-cyanophenyl)-2-propanone (35): mp 144–145 °C; IR (KBr) 2210 (C≡N), 1720 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 4.10 (s, CH_2, 4 H), 7.20–7.65 (m, arom, 8 H); mass spectrum, m/e 260.0949, calcd for $C_{17}H_{12}N_2O$ 260.0951. Anal. Calcd for $C_{17}H_{12}N_2O$: C, 78.44; H, 4.65; N, 10.76. Found: C, 78.45; H, 4.82; N, 10.74.

1,3-Bis(4-cyanophenyl)-2-propanone (36): mp 150–150.5 °C; IR (KBr) 2215 (C≡N), 1710 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 3.84 (s, CH_2, 4 H), 7.28 (d, J = 8.5 Hz, arom, 4 H), 7.60 (d, J = 8.5 Hz, arom, 4 H); mass spectrum, m/e 260 (M^+). Anal. Calcd for $C_{17}H_{12}N_2O$: C, 78.44; H, 4.65; N, 10.76. Found: C, 78.65; H, 4.47; N, 10.61.

Reaction of Benzoyl Chloride with Acrylonitrile or 3-Buten-2-one in the Presence of Metallic Nickel. Metallic nickel was prepared from nickel iodide (3.79 g, 12.1 mmol), lithium (0.193 g, 27.9 mmol), and naphthalene (0.155 g, 1.20 mmol) in glyme (30 mL) as described above. The nickel in glyme was heated to reflux, a mixture of benzoyl chloride (2.64 g, 18.8 mmol), and acrylonitrile (1.29 g, 24.2 mmol) in glyme (10 mL) was added for 30 min and additional heating was continued for 30 min. After being cooled, the reaction mixture was poured into a separatory funnel containing hydrochloric acid solution (3%, 100 mL) and extracted with chloroform twice. The chloroform solution was washed with water, and the aqueous phase was extracted with chloroform. The combined extracts were dried over anhydrous sodium sulfate and concentrated. Crude oil was chromatographed on silica gel eluted with chloroform to give 4-phenyl-4-oxobutanenitrile (**37**, 0.541 g, 18%). **37**: mp 73.5–74 °C (lit.[83] mp 70 °C); IR (KBr) 2240 (C≡N), 1680 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 2.75 (t, J = 7 Hz, CH_2CN, 2 H), 3.38 (t, J = 7 Hz, CH_2CO, 2 H), 7.30–7.77 (m, arom, 3 H), 7.85–8.10 (m, arom, 2 H). Spectral data were consistent with those reported.[83]

The reaction of benzoyl chloride with 3-buten-2-one in the presence of metallic nickel was carried out in a similar manner and 1-phenyl-1,4-pentanedione (**38**) was isolated in 14% yield. **38**: bp 100 °C (0.42 mmHg) [lit.[84] bp 113 °C (0.1 mmHg)]; IR (neat) 1710 (C=O), 1680 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 2.22 (s,

(71) Blanco, F. E.; Harris, F. L. *J. Org. Chem.* **1977**, *42*, 868.
(72) Mulvaney, J. E.; Carr, L. J. *J. Org. Chem.* **1968**, *33*, 3286.
(73) Huttel, R.; Franke, K.; Martin, H.; Riedl, J. *Chem. Ber.* **1960**, *93*, 1433.
(74) Ferreira, A. B. B.; Salisbury, K. *J. Chem. Soc., Perkin Trans. 2* **1978**, 995.
(75) Eistert, B.; Juraszyk, H.; Arackal, T. J. *Chem. Ber.* **1976**, *109*, 640.
(76) Konieczny, W. *Arch. Immunol. Ter. Dosw.* **1961**, *9*, 599; *Chem. Abstr.* **1963**, *59*, 5845.
(77) Craig, J. T.; McNatty, K. P. *Aust. J. Chem.* **1967**, *20*, 1921.
(78) Newman, M. S.; O'Leary, T. J., Jr. *J. Am. Chem. Soc.* **1946**, *68*, 258.
(79) Newman, M. S.; Mangham, J. R. *J. Am. Chem. Soc.* **1949**, *71*, 3342.
(80) Wissner, A. *J. Org. Chem.* **1979**, *44*, 4617.
(81) Rapoport, H.; Bonner, R. M. *J. Am. Chem. Soc.* **1950**, *72*, 2783.
(82) Beckert, W. F.,; Lowe, J. U., Jr. *J. Org. Chem.* **1967**, *32*, 582.
(83) Yoshisato, E.; Ryang, M.; Tsutsumi, S. *J. Org. Chem.* **1969**, *34*, 1500.
(84) Bellassoued, M.; Dardoize, F.; Gaudemar, M. *J. Organomet. Chem.* **1979**, *177*, 35.

CH_3, 3 H), 2.84 (t, J = 6 Hz, CH_2COCH_3, 2 H), 3.26 (t, J = 6 Hz, CH_2COAr, 2 H), 7.20–7.75 (m, arom, 3 H), 7.90–8.20 (m, arom, 2 H); spectral data were consistent with those reported.[84]

1-Phenyl-3-buten-1-one (43): bp 61 °C (0.47 mmHg) [lit.[85] bp 100–102 °C (5 mmHg)]; IR (neat) 1680 (C=O), 1635 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 3.73 (d of t, J = 7 and 1.5 Hz, CH_2, 2 H), 5.18 (d of d of t, J = 16.5, 1.5, and 1.5 Hz, *trans*-HC=CHC, 1 H), 5.25 (d of d of t, J = 11, 1.5, and 1.5 Hz, *cis*-HC=CHC, 1 H), 5.85–6.40 (m, $CHCH_2$, 1 H), 7.30–7.70 (m, arom, 3 H), 7.70–8.20 (m, arom, 2 H).

***trans*-1-Phenyl-2-buten-1-one (44)**: bp 59 °C (0.19 mmHg) [lit.[86] bp 84–85 °C (0.5 mmHg)]; IR (neat) 1665 (C=O), 1615 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 1.94 (d, J = 6 Hz, CH_3, 3 H), 6.84 (d, J = 15.5 Hz, HCCO, 1 H), 7.07 (d of q, J = 15.5 and 6 Hz, $HCCH_3$, 1 H), 7.20–7.65 (m, arom, 3 H), 7.73–8.07 (m, arom, 2 H).

1-Cyclohexyl-3-buten-1-one (45): bp 89 °C (10 mmHg); IR (neat) 1700 (C=O), 1635 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 0.80–2.10 (m, CH_2, 10 H), 2.10–2.57 (m, CH, 1 H), 3.18 (d of t, J = 7 and 1.5 Hz, CH_2, 2 H), 5.08 (d of d of t, J = 16.5, 1.5, and 1.5 Hz, *trans*-HC=CHC, 1 H), 5.13 (d of d of t, J = 10, 1.5, and 1.5 Hz, *cis*-HC=CHC, 1 H), 5.67–6.23 (m, $=CHCH_2$, 1 H); mass spectrum, m/e 152.1204, calcd for $C_{10}H_{16}O$ 152.1188. Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 79.04; H, 10.69.

***trans*-1-Cyclohexyl-2-buten-1-one (46)**: bp 98 °C (10.5 mmHg); IR (neat) 1685, 1660, 1625 cm^{-1} (C=O, C=C); NMR ($CDCl_3$) δ 0.70–2.10 (m, CH_2, 10 H), 1.88 (d of d, J = 6.5 and 1.5 Hz, CH_3, 3 H), 2.20–2.75 (m, CH, 1 H), 6.18 (d of q, J = 16 and 1.5 Hz, =CHCO, 1 H), 7.87 (d of d, J = 16 and 6.5 Hz, CH, 1 H); mass spectrum, m/e 152.1196. Calcd $C_{10}H_{16}O$ 152.1229. Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 79.08; H, 10.36.

1-Phenyl-3-methyl-3-buten-1-one (47): bp 113 °C (10.5 mmHg) [lit.[87] bp 80 °C (0.01 mmHg)]; IR (neat) 1680 (C=O), 1645 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 1.82 (d, J = 1 Hz, CH_3, 3 H), 3.68 (s, CH_2, 2 H), 4.80–4.91 (m, CH, 1 H), 4.91–5.05 (m, CH, 1 H), 7.27–7.70 (m, arom, 3 H), 7.83–8.17 (m, arom, 3 H).

1-Phenyl-3-methyl-2-buten-1-one (48): bp 133 °C (16 mmHg) [lit.[88] bp 136–138 °C (15 mmHg)]; IR (neat) 1655 (C=O), 1610 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 2.00 (d, J = 1.2 Hz, CH_3, 3 H), 2.21 (d, J = 1.2 Hz, CH_3, 3 H), 6.67–6.83 (m, CH, 1 H), 7.25–7.65 (m, arom, 3 H), 7.75–8.13 (m, arom, 2 H).

***trans*-1,4-Diphenyl-3-buten-1-one (49)**: mp 91.5–92 °C (lit.[89] 92–93 °C); IR (KBr) 1675 cm^{-1} (C=O and C=C); NMR ($CDCl_3$) δ 3.80–4.00 (m, CH_2, 2 H), 6.43 (d of d, J = 16 and 7.5 Hz, CH, 1 H), 6.57 (d, J = 16 Hz, 1 H), 7.13–7.70 (m, arom, 8 H), 7.85–8.15 (m, arom, 2 H).

***trans*-1-Phenyl-1-undecen-4-one (50)**: bp 125 °C (0.09 mmHg); IR (neat) 1705 (C=O), 1665 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 0.88 (t, J = 6 Hz, CH_3, 3 H), 1.05–1.70 (m, CH_2, 10 H), 2.47 (t, J = 7 Hz, CH_2CO, 2 H), 3.28 (d, J = 6 Hz, $=CCH_2$, 2 H), 6.27 (d of d, J = 16 and 6 Hz, =CH, 1 H), 6.50 (d, J = 16 Hz, =CH, 1 H), 7.05–7.50 (m, arom, 5 H). Anal. Calcd for $C_{17}H_{24}O$: C, 83.55; H, 9.90. Found: C, 83.55; H, 10.09.

***trans*-Methyl 5-oxo-8-phenyl-7-octenoate (51)**: bp 148 °C (0.18 mmHg); IR (neat) 1730 (C=O), 1705 (C=O), 1665 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 1.88 (q, J = 7 Hz, CH_2, 2 H), 2.32 (t, J = 7 Hz, CH_2CO_2, 2 H), 2.53 (t, J = 7 Hz, CH_2CO, 2 H), 3.27 (d, J = 6 Hz, $=CCH_2$, 2 H), 3.63 (s, CH_3, 3 H), 6.27 (d of d, J = 15.5 and 6 Hz, =CH, 1 H), 6.47 (d, J = 15.5 Hz, =CH, 1 H), 7.00–7.50 (m, arom, 5 H). Anal. Calcd for $C_{15}H_{18}O_3$: C, 75.13; H, 7.37. Found: C, 72.91; H, 7.57.

***trans*-4-Phenyl-3-buten-2-one (52)**: mp 40.5–41.5 °C; bp 73 °C (0.30 mmHg) [lit.[90] mp 40–42 °C; bp 123–128 °C (8 mmHg)]; IR (KBr) 1670 (C=O), 1590 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 2.37 (s, CH_3, 3 H), 6.70 (d, J = 16.5 Hz, =CH, 1 H), 7.27–7.70 (m, arom, 5 H), 7.53 (d, J = 16.5 Hz, =CH, 1 H).

***trans*-1-Phenyl-1-decen-3-one (53)**: mp 50–50.5 °C (lit.[91] mp 51–52 °C); IR (KBr) 1660 (sh), 1640, 1620 cm^{-1} (C=O, C=C); NMR ($CDCl_3$) δ 0.89 (t, J = 6 Hz, CH_3, 3 H), 1.05–2.00 (m, CH_2, 10 H), 2.64 (t, J = 7.5 Hz, CH_2CO, 2 H), 6.77 (d, J = 16.5 Hz, =CH, 2 H), 7.05–7.73 (m, arom and =CH, 6 H).

***trans*-1-Cyclohexyl-3-phenyl-2-propen-1-one (54)**: mp 57.5–58 °C; bp 122 °C (0.28 mmHg) [lit.[92] mp 56–56.5 °C; lit.[93] bp 122–124 °C (0.06 mmHg)]; IR (KBr) 1675 (C=O), 1600 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 1.00–2.10 (m, CH_2, 10 H), 2.40–2.90 (m, CH, 1 H), 6.82 (d, J = 17 Hz, =CH, 1 H), 7.20–7.82 (m, arom and =CH, 6 H).

***trans*-1-Phenyl-5-methyl-1,4-hexadien-3-one (55)**: bp 118 °C (0.56 mmHg) [lit.[94] bp 130–133 °C (0.7 mmHg)]; IR (neat) 1665, 1645, 1620, 1590 cm^{-1} (C=O, C=C); NMR ($CDCl_3$) δ 1.94 (s, CH_3, 3 H), 2.23 (s, CH_3, 3 H), 6.38 (br s, CH, 1 H), 6.83 (d, J = 16.5 Hz, CH, 1 H), 7.15–7.85 (m, arom and CH, 6 H)

***trans*-Methyl 5-oxo-7-phenyl-6-hexenoate (56)**: mp 57–57.5 °C; bp 125 °C (0.11 mmHg); IR (KBr) 1725, 1660 (sh), 1640, 1620 cm^{-1} (C=O, C=C); NMR ($CDCl_3$) δ 2.00 (q, J = 7 Hz, CH_2, 2 H), 2.41 (t, J = 7 Hz, CH_2CO_2, 2 H), 2.74 (t, J = 7 Hz, CH_2CO, 2 H), 3.69 (s, CH_3, 3 H), 6.75 (d, J = 17 Hz, CH, 1 H), 7.27–7.75 (m, arom and CH, 6 H). Anal. Calcd for $C_{14}H_{16}O_3$: C, 72.39; H, 6.94. Found: C, 72.12; H, 6.87.

2,3,4,5,6-Pentafluorobenzophenone (57): bp 137 °C (12 mmHg) [lit.[95] 93 °C (0.2 mmHg)]; IR (neat) 1690 cm^{-1} (C=O); NMR ($CDCl_3$) δ 7.33–8.00 (m, arom, 5 H).

4-Chloro-2',3',4',5',6'-pentafluorobenzophenone (58): mp 63–63.5 °C; bp 93 °C (0.12 mmHg); IR (KBr) 1680 cm^{-1} (C=O); NMR ($CDCl_3$) δ 7.60 (d, J = 9 Hz, arom, 2 H), 7.81 (d, J = 9 Hz, arom, 2 H). Anal. Calcd for $C_{13}H_4ClF_5O$: C, 50.92; H, 1.32. Found: C, 51.24; H, 1.44.

1-(Pentafluorophenyl)-1-octanone (59): bp 67 °C (0.11 mmHg); IR (neat) 1710 cm^{-1} (C=O); NMR ($CDCl_3$) δ 0.88 (t, J = 6 Hz, CH_3, 3 H), 1.00–1.95 (m, CH_2, 10 H), 2.85 (t, J = 7 Hz, CH_2CO, 2 H). Anal. Calcd for $C_{14}H_{15}F_5O$: C, 54.14; H, 5.14. Found: C, 57.30; H, 5.21.

Pentafluorophenyl cyclohexyl ketone (60): mp 43.5–44 °C; bp 135 °C (16 mmHg); IR (KBr) 1700 cm^{-1} (C=O); NMR ($CDCl_3$) δ 1.00–2.17 (m, CH_2, 10 H), 2.57–3.00 (m, CH, 1 H). Anal. Calcd for $C_{13}H_{11}F_5O$: C, 56.12; H, 3.98. Found: C, 56.33; H, 3.90.

Methyl 5-oxo-5-(pentafluorophenyl)pentanoate (61): bp 77 °C (0.11 mmHg); IR (neat) 1730 (C=O), 1710 (C=C) cm^{-1}; NMR ($CDCl_3$) δ 2.05 (q, J = 7.5 Hz, CH_2, 2 H), 2.43 (t, J = 7.5 Hz, CH_2CO_2, 2 H), 2.97 (t, J = 7.5 Hz, CH_2CO, 2 H), 3.67 (s, CH_3, 3 H). Anal. Calcd for $C_{12}H_9F_5O_3$: C, 48.66; H, 3.06. Found: C, 48.57; H, 3.09.

Acknowledgment. We gratefully acknowledge support of this work by the Division of Chemical Sciences, Department of Energy (Contract No. DE-AC02-80ER10603).

Registry No. **1**, 451-40-1; **2**, 1889-71-0; **3**, 103-79-7; **4**, 32508-90-0; **5**, 61259-29-8; **6**, 38661-84-6; **7**, 61799-54-0; **8**, 86607-65-0; **9**, 65248-41-1; **10**, 54723-26-1; **11**, 54276-99-2; **12**, 2042-85-5; **13**, 2430-99-1; **14**, 30934-66-8; **15**, 29955-26-8; **16**, 347-91-1; **17**, 6332-83-8; **18**, 16897-97-5; **19**, 22421-88-1; **20**, 6186-22-7; **21**, 73013-48-6; **22**, 58949-75-0; **23**, 94161-45-2; **24**, 15482-54-9; **25**, 86896-46-0; **26**, 16216-08-3; **27**, 33744-50-2; **28**, 21567-68-0; **29**, 29417-89-8; **30**, 102-04-5; **31**, 70769-70-9; **32**, 18925-69-4; **33**, 7484-19-7; **34**, 89654-16-0; **35**, 95123-12-9; **36**, 29903-10-4; **37**, 5343-98-6; **38**, 583-05-1; **43**, 6249-80-5; **44**, 35845-66-0; **45**, 95123-13-0; **46**, 15378-40-2; **47**, 52813-35-1; **48**, 5650-07-7; **49**, 3420-52-8; **50**, 95123-14-1; **51**, 95123-15-2; **52**, 1896-62-4; **53**, 95123-16-3; **54**, 84319-69-7; **55**, 79629-17-7; **56**, 95123-17-4; **57**, 1536-23-8; **58**, 95123-18-5; **59**, 95123-19-6; **60**, 95123-20-9; **61**, 95123-21-0; $NiCl_2$, 7718-54-9; $NiBr_2$, 13462-88-9; NiI_2, 13462-90-3; Ni, 7440-02-0; $C_6H_5CH_2Cl$, 100-44-7; $C_6H_5CH_2Br$, 100-39-0; C_6H_5COCl, 98-88-4; C_6H_5COBr, 618-32-6; $3\text{-}CF_3C_6H_4CH_2Cl$, 705-29-3;

(85) Bohlmann, F.; Stohr, F.; Staffeldt, J. *Chem. Ber.* **1978**, *111*, 3146.
(86) Reich, H. J.; Renga, J. M.; Reich, I. L. *J. Am. Chem. Soc.* **1975**, *97*, 5434.
(87) Jager, V.; Grund, H.; Schwab. W. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 78.
(88) Gaheiz, G.; Bernard, D.; Normant, J. F. *Synthesis* **1977**, 130.
(89) Padwa, A.; Crumrine, D.; Hartman, R.; Layton, R. *J. Am. Chem. Soc.* **1967**, *89*, 4435.
(90) Drake, N. L.; Allen, P., Jr. "Organic Syntheses"; Wiley: New York, 1941; Coll. Vol. 1, p 77.
(91) Heilbron, I. M.; Irving, F. *J. Chem. Soc.* **1929**, 931.
(92) Mariella, P. P.; Raube, R. R. *J. Am. Chem. Soc.* **1952**, *74*, 521.
(93) Portnoy, N. A.; Morrow, C. J.; Chattha, M. S.; Williams, J. C., Jr.; Agular, A. M. *Tetrahedron Lett.* **1971**, 1401.
(94) Ramalingam, K.; Berlin, K. D.; Loghry, R. A.; van der Helm, D.; Satyamurthy, N. *J. Org. Chem.* **1979**, *44*, 477.
(95) Schmeisser, M.; Weidenbruch, M. *Chem. Ber.* **1967**, *100*, 2306.

3-$CH_3OC_6H_4CH_2Cl$, 824-98-6; 4-$FC_6H_4CH_2Cl$, 352-11-4; 4-$ClC_6H_4CH_2Cl$, 104-83-6; 2-$BrC_6H_4CH_2Br$, 3433-80-5; 4-$BrC_6H_4CH_2Br$, 589-15-1; 2-$NCC_6H_4CH_2Br$, 22115-41-9; 4-$NCC_6H_4CH_2Br$, 17201-43-3; $C_6H_5CH(CH_3)Cl$, 672-65-1; 4-$CH_3C_6H_4CH_2Cl$, 104-82-5; 4-$CH_3OCOC_6H_4CH_2Cl$, 34040-64-7; 4-$HOCOC_6H_4CH_2Br$, 6232-88-8; 3-$BrCH_2C_6H_4CH_2Br$, 626-15-3; 4-ClC_6H_4COCl, 122-01-0; CH_3COCl, 75-36-5; $CH_3(CH_2)_6COCl$, 111-64-8; *trans*-$C_6H_5CH{=}CHCOCl$, 17082-09-6; $(CH_3)_2C{=}CHCOCl$, 3350-78-5; $CH_3OCOCH_2CH_2COCl$, 1490-25-1; $CH_3OCOCH_2CH_2CH_2COCl$, 1501-26-4; $ClCOCH_2CH_2COCl$, 543-20-4; CH_3OCH_2COCl, 38870-89-2; $C_6H_5COCOCl$, 25726-04-9; $(CH_3)_2NCOCl$, 79-44-7; C_6F_5COCl, 2251-50-5; $ClCOCOCl$, 79-37-8; $C_6H_5CH_2CH_2C_6H_5$, 103-29-7; $NCCH{=}CH_2$, 107-13-1; $CH_3COCH{=}CH_2$, 78-94-4; $H_2C{=}CHCH_2Br$, 106-95-6; $H_2C{=}C(CH_3)CH_2Cl$, 563-47-3; *trans*-$C_6H_5CH{=}CHCH_2Br$, 26146-77-0; *trans*-$CH_3CH{=}CHBr$, 590-15-8; *cis*-$CH_3CH{=}CHBr$, 590-13-6; *trans*-$C_6H_5CH{=}CHBr$, 588-72-7; C_6F_5I, 827-15-6; (1-naphthyl)chloromethane, 86-52-2; (2-naphthyl)bromomethane, 939-26-4; cyclohexylcarbonyl chloride, 2719-27-9; 2-furylcarbonyl chloride, 527-69-5.

Stereochemistry of the Hydride Reduction of 7-Oxabicyclo[2.2.1]heptanes

Randall J. Moss and Bruce Rickborn*

Department of Chemistry, University of California, Santa Barbara, California 93106

Received July 9, 1984

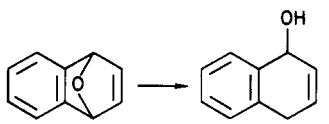
The reductive cleavage, by $LiAlD(O\text{-}t\text{-}Bu)_3/Et_3B$, of two 7-oxabicyclo[2.2.1]heptanes is found to occur with high inversion stereospecificity (≥96% and ≥98%, respectively). The substrates were chosen to present potential complicating factors, but the reactions occur cleanly by hydride (deuteride) attack at the cleaved center, suggesting that this stereochemical result will prove to be general for reduction of 1,4-epoxides. The conditions are mild enough to allow isolation of the "arene hydrate" 1-hydroxy-1,4-dihydronaphthalene from the reduction of 1,4-epoxy-1,4-dihydronaphthalene. The reaction provides a useful way to introduce deuterium stereospecifically, by reduction of isobenzofuran cycloadducts and related materials.

Brown and co-workers have shown that the potent reducing agent obtained by mixing lithium tri-*tert*-butoxyaluminohydride (LTBAH) and triethylborane efficiently cleaves certain types of ethers, e.g., THF and methoxyaliphatics.[1] The reagent is thought to consist of lithium triethylborohydride (Super-Hydride) and aluminum tri-*tert*-butoxide, with the latter species providing the electrophilic activation of the ether needed for facile cleavage. In keeping with this view, a mixture of LTBAH and catalytic triethylborane (10%) also effects such reductions.[1] Although electrophilic assistance is critical for reaction, product analyses from unsymmetrical ethers suggest an overall S_N2-like mechanism; i.e., hydride attack occurs preferentially at the less substituted carbon. The reduction of 1-methylcyclohexene oxide is informative; the tertiary alcohol is the major product (90%), while the minor product (10%, indicative of a strong electrophilic component) is *cis*-2-methylcyclohexanol, with the stereochemistry required of an S_N2 displacement.

We were intrigued by the observation[1] that 7-oxabicyclo[2.2.1]heptane is rapidly reduced to cyclohexanol by the mixed reagent. If this proved to be a general reaction of this ring system, it offered a potentially useful way to convert cycloadducts of isobenzofurans and related materials to the corresponding alcohols. Further, if such reductions were stereospecific, a novel method for hydrogen isotope incorporation at the remote site would be available.

Results and Discussion

The readily available cycloadduct of benzyne and furan, **1**, is an interesting substrate for testing the generality of the reduction. Since the ethereal bonds are both benzylic and allylic, **1** is expected to be especially susceptible to electrophile-induced cation formation and possible rearrangement. Also, Caple et al. have reported that **1** reacts with alkyllithium reagents at the double bond, leading, via oxa-ring opening, to *cis*-1,2-dihydro-2-alkylnaphthalenols,[2] and analogous attack by hydride represents another possible complication. However, we find that **1** reacts smoothly with LTBAH/20% triethylborane in tetrahydropyran (THP) solvent to give alcohol **2**, the anticipated product of direct reduction of the ether linkage.



1 **2** (1)

This deceptively simple-appearing product has been reported only once previously, formed by sulfite reduction of the hydroperoxide generated by autoxidation of 1,4-dihydronaphthalene.[3] Later workers[4] were unable to reproduce this finding, leaving some doubt about the earlier claim (the melting point of our **2**, however, coincides with that in the literature[3]). Compound **2** is a member of the so-called "arene hydrates"[5] and, as expected, exotherms on treatment with acid to form water and naphthalene. It can be recrystallized from hydrocarbon solvent (mp 46–47 °C) and has been successfully stored for several weeks at −10 °C. NMR spectra have been obtained in $CDCl_3$, although dehydration, presumably trace acid catalyzed, has been observed with some samples kept in this solvent.

In connection with ongoing studies of 1,4-elimination, we were particularly interested in converting **2** to the methyl ether derivative **3**. Attempts to do so with

(1) Brown, H. C.; Krishnamurthy, S.; Coleman, R. A. *J. Am. Chem. Soc.* **1972**, *94*, 1750. Krishnamurthy, S.; Brown, H. C. *J. Org. Chem.* **1979**, *44*, 3678.

(2) Caple, R.; Chen, G. M. S.; Nelson, J. D. *J. Org. Chem.* **1971**, *36*, 2874. See also: Jeffrey, A. M.; Yeh, H. J. C.; Jerina, D. M.; DeMarinis, R. M.; Foster, C. H.; Piccolo, D. E.; Berchtold, G. A. *J. Am. Chem. Soc.* **1974**, *96*, 6929. Brion, F. *Tetrahedron Lett.* **1982**, 5299.

(3) Hock, H.; Depke, F. *Chem. Ber.* **1950**, *83*, 327.

(4) Jeffrey, A. M.; Jerina, D. M. *J. Am. Chem. Soc.* **1972**, *94*, 4048.

(5) Staroscik, J.; Rickborn, B. *J. Am. Chem. Soc.* **1971**, *93*, 3046.

0022-3263/85/1950-1381$01.50/0