Highly Regio- and Stereoselective Cocyclotrimerization and Linear Cotrimerization of α,β-Unsaturated Carbonyl Compounds with Alkynes Catalyzed by Nickel Complexes

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Cyclic enones 2-cyclohexen-1-one (**1a**), 4,4-dimethyl-2-cyclohexen-1-one (**1b**), 2-cyclopenten-1-one (**1c**), and 2-cyclohepten-1-one (**1d**) react with octa-1,7-diyne (**2**) in THF in the presence of $Ni(PPh_3)_2I_2$, ZnI_2, and Zn powder at 62 °C to give [2 + 2 + 2] cycloaddition−dehydrogenation products **3a**−**d** in 32−80% yields. α,β-Unsaturated lactone **5a** (5,6-dihydro-2*H*-pyran-2-one) undergoes [2 + 2 + 2] cycloaddition with **2** to give both the corresponding cyclohexadiene product **6** (29%) and dehydrogenation product **7** (39%). Under similar reaction conditions, 3-buten-2-one reacts with **2** and various substituted hepta-1,6-diynes **9a**−**c** to give [2 + 2 + 2] cycloaddition−dehydrogenation products **11a**−**d** in 68−80% yields. Diphenylacetylene also reacts with **1a**−**d**, **5a**, and 2(5*H*)-furanone (**5b**) to afford the corresponding [2 + 2 + 2] cocyclotrimerization products **13a**−**d** and **14a**−**b**. No dehydrogenation of products **13** and **14** was observed under the reaction and workup conditions. The reactions of acrylates with alkynes catalyzed by nickel complexes give products that depend greatly on the reaction conditions. Treating ethyl acrylate (**15a**) with 1-phenyl-1-propyne (**16**) in the presence of $Ni(PPh_3)_2Cl_2$ and Zn at 90 °C in toluene affords cocyclotrimerization product **19a** as the major product (54% yield). However, treatment of $CH_2CHCOOR$ (R = Et and *t*-Bu) with mono alkynes **16** and **12** in the presence of $Ni(PPh_3)_2X_2$ (X = Cl and I) and Zn powder in toluene at 60 °C affords the corresponding conjugated trienes **17a**−**c** in 82−92% yields. The MS data of **17** firmly support an adduct of two molecules of alkyne and a molecule of acrylate. Similarly, the reaction of **15a** with octa-1,7-diyne in the presence of $Ni(PPh_3)_2I_2$, ZnI_2, and zinc gives triene derivative **21** in 68% yield. NOE and X-ray results indicate that in these trienes the substituents from each alkyne and alkene moiety are cis to each other. The unique stereoselectivity can be attributed to the exclusive formation of seven-membered nickelacycloheptadiene intermediate **25** during the catalytic reaction.

Introduction

Metal-catalyzed cocyclotrimerization of unsaturated compounds with alkynes is a powerful synthetic method for the construction of polycyclic compounds.[1−3] Cocyclotrimerization of aldehydes,[4] carbon dioxide,[5] and isocyanides[6] with alkynes mediated by transition-metal complexes are known. Recently, we reported a nickel-catalyzed cocyclotrimerization of an oxa- or azabenzonorbornadiene or C_{60} fullerene with two alkynes to afford multiple-ring products.[7] Ikeda et al.[8] described the cocyclotrimerization of cyclic enones with mono alkynes using $Ni(acac)_2/PPh_3/Al(Me)_3$ as the catalyst system and cocyclotrimerization of 3-buten-2-one and 2-cyclohexen-1-one with 1,6-heptadiynes catalyzed by $NiCl_2/ZnCl_2/Zn$ to give [2 + 2 + 2] cyclic products. In an independent study,[9] we used $Ni(PPh_3)_2X_2/Zn/(ZnI_2)$ as catalyst systems for cocyclotrimerization and linear cotrimerization of enones and acrylates with alkynes. The nickel systems employed successfully catalyze the cocyclotrimerization of cyclic enones and α,β-unsaturated lactones with diynes to give the corresponding tricyclic products.[9a] Moreover, these systems catalyze linear trimerization of acrylates with alkynes to give conjugated trienes.[9b] This new triene formation reaction is highly regio- and stereoselective. Triene functionality is important in organic synthesis and in natural products.[10] This catalytic reaction provides a unique method for the synthesis of trienes in which the substituents from each alkyne and alkene moiety are cis to each other. Herein, we report the results of these studies.

(1) (a) Vollhardt, K. P. C. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 539. (b) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829. (c) Nugent, W. A.; Thorn, D. L.; Harlow, R. L. *J. Am. Chem. Soc.* **1987**, *109*, 2788.

(2) (a) Chalk, A. J. *J. Am. Chem. Soc.* **1972**, *94*, 5928. (b) Suzuki, H.; Itoh, K.; Ishii, Y.; Simon, k.; Ibers, J. A. *J. Am. Chem. Soc.* **1976**, *98*, 8494. (c) Balaich, G. J.; Rothwell, I. P. *J. Am. Chem. Soc.* **1993**, *115*, 1581.

(3) (a) Zhou, Z.; Battaglia, L. P.; Chiusoli, G. P.; Costa, M.; Nardelli, M.; Pelizzi, C.; Predieri, G. *J. Chem. Soc., Chem. Commun.* **1990**, 1632. (b) Zhou, Z.; Costa, M.; Chiusoli, G. P. *J. Chem. Soc., Perkin Trans. 1* **1992**, 1399. (c) Grigg, R.; Scott, R.; Stevenson, P. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1365.

(4) (a) Tsuda, T.; Kumisada, K.; Nagakama, M.; Morihara, S.; Saegusa, T. *Synth. Commun.* **1989**, *19*, 1575. (b) Tsuda, T.; Kiyoi, T.; Miyane, T.; Saegusa, T. *J. Am. Chem. Soc.* **1988**, *110*, 8570.

(5) (a) Tsuda, T.; Sumiya, R.; Saegusa, T. *Synth. Commun.* **1987**, *17*, 147. (b) Tsuda, T.; Morihara, S.; Sumiya, R.; Saegusa, T. *J. Org. Chem.* **1988**, *53*, 3140. (c) Tsuda, T.; Morihara, S.; Saegusa, T. *J. Chem. Soc., Chem. Commun.* **1989**, 9.

(6) Tamao, K.; Kobayashi, K.; Ito, Y. *J. Org. Chem.* **1989**, *54*, 3517.

(7) (a) Huang, D.-J.; Sambaiah, T.; Cheng, C.-H. *New J. Chem.* **1998**, *22*, 1147. (b) Hsiao, T.-Y.; Santhosh, K. C.; Liou, K.-F.; Cheng, C.-H. *J. Am. Chem. Soc.* **1998**, *120*, 12232.

(8) (a) Ikeda, S.; Mori, N.; Sato, Y. *J. Am. Chem. Soc.* **1997**, *119*, 4779. (b) Appeared during our manuscript preparation: Ikeda, S.; Watanabe, H.; Sato, Y. *J. Org. Chem.* **1998**, *63*, 7026.

(9) Part of the material of (a) cocyclotrimerization was extracted from the Ph.D. Thesis of D.-J. Huang, submitted to National Tsing Hua University, Hsinchu, Taiwan, ROC, 1994. (b) Linear cotrimerization in this paper was from the Ph.D. Thesis of Lih-Ping Li, 1998.

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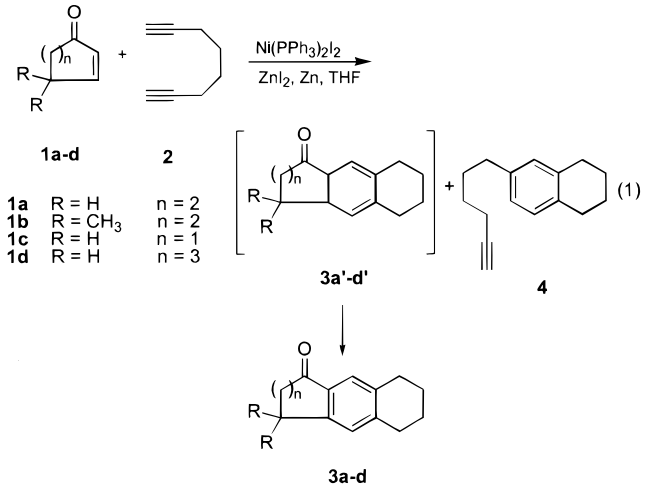
Table 1. Effects of Nickel Catalysts, Lewis Acids, and Solvents on the Cocyclotrimerization of 2-Cyclohexen-1-one with Octa-1,7-diyne[a]

entry	solvent	temp (°C)	catalyst	product **3a** (yield, %)[b]
1	THF	62	$NiCl_2(PPh_3)_2$	10
2	THF	62	$NiCl_2(PPh_3)_2$, ZnI_2	60
3	THF	62	$NiCl_2(PPh_3)_2$, $ZnCl_2$	32
4	THF	62	$NiCl_2(PPh_3)_2$, CuCl	24
5	THF	62	$NiCl_2(PPh_3)_2$, CuI	30
6	THF	62	$NiCl_2(PPh_3)_2$, LiCl	trace
7	THF	62	$NiCl_2(PPh_3)_2$, $MgCl_2$	33
8	THF	62	$NiCl_2(PPh_3)_2$, BF_3	17
9	THF	62	$NiBr_2(PPh_3)_2$, ZnI_2	73
10	THF	62	$NiI_2(PPh_3)_2$, ZnI_2	80
11	toluene	62	$NiI_2(PPh_3)_2$, ZnI_2	17
12	CH_2Cl_2	25	$NiI_2(PPh_3)_2$, ZnI_2	trace
13	CH_3CN	80	$NiI_2(PPh_3)_2$, ZnI_2	10
14	THF	62	$NiI_2(PPh_3)_2$, $(C_4H_9)_4NI$	0

[a] Reaction condition: 2-cyclohexen-1-one (1.00 mmol), octa-1,7-diyne (1.50 mmol), nickel catalyst (0.0500 mmol), Lewis acid (0.0500 mmol), Zn (2.75 mmol), and THF (2.00 mL) at 62 °C for 4 h. See Experimental Section for detailed procedure. [b] Isolated yields.

Results and Discussion

Treatment of 2-cyclohexen-1-one (**1a**) in the presence of $Ni(PPh_3)_2Cl_2$ and Zn powder in THF with octa-1,7-diyne (**2**) by slow addition with a syringe pump at 62 °C afforded a [2 + 2 + 2] cyclotrimerization product **3a** (eq 1) in 10% yield (entry 1, Table 1). Slow addition of **2** is



necessary; if **1a** and diyne **2** were completely mixed prior to the catalytic reaction, essentially no product **3a** was observed, but compound **4**, a dimer of diyne **2** was isolated as the major product. Compound **3a** is produced from a [2 + 2 + 2] cocyclotrimerization of **1a** and **2** to give a cyclohexadiene derivative **3a′**, followed by dehydrogenation of **3a′**. In an effort to further improve the efficiency of this reaction, we found that the yield of product **3a** increased on addition of a catalytic amount of Lewis acid to the above reaction. Several Lewis acids were tested, and the results are summarized in Table 1. Among these Lewis acids employed, ZnI_2 is most effective,

Table 2. Nickel-Catalyzed Cocyclotrimerization of Cyclic Enones and Lactones with Octa-1,7-diyne and Diphenylacetylene

entry	enone[a]	solvent	time (h)	temp (°C)	product (yield %)[b]
1	**1b**	THF	4	62	 **3b** (45)
2	**1c**	THF	4	62	 **3c** (32)
3	**1d**	THF	4	62	 **3d** (51)
4	**5a**	THF	4	62	 **6** (29)  **7** (39)
5	**1a**	CH_2Cl_2	20	25	 **13a** (84)
6	**1b**	THF	24	60	 **13b** (60)
7	**1c**	CH_2Cl_2	24	42	 **13c** (86)
8	**1d**	THF	18	60	 **13d** (20)
9	**5a**	THF	24	60	 **14a** (78)
10	**5b**	THF	48	60	 **14b** (28)

[a] Reaction conditions: cyclic enone or lactone (1.00 mmol), diphenylacetylene (2.00 mmol) or 1,7-octadiyne (1.50 mmol), $NiI_2(PPh_3)_2$ (0.0500 mmol), ZnI_2 (0.0500 mmol), Zn (2.75 mmol), and solvent (4.00 or 2.00 mL). See Experimental Section for detailed procedure. [b] Isolated yields.

giving product **3a** in 60% yield using $Ni(PPh_3)_2Cl_2$ as the catalyst (entry 2, Table 1). Other Lewis acids such as $ZnCl_2$, CuI, $MgCl_2$, CuCl, and BF_3 also increase the yield of **3a** but are less effective than ZnI_2. It is noteworthy that the presence of LiCl or $(Bu)_4NI$ in the reaction greatly inhibits the formation of **3a** (entry 6 and 14, Table 1).

In addition to $Ni(PPh_3)_2Cl_2$, $Ni(PPh_3)_2Br_2$, and $Ni(PPh_3)_2I_2$ are also active catalysts for the [2 + 2 + 2] cyclotrimerization of **1a** and **2**. In fact, $Ni(PPh_3)_2Br_2/ZnI_2$/Zn and $Ni(PPh_3)_2I_2/ZnI_2$/Zn systems give **3a** in 73 and 80% yields, respectively (entries 9 and 10, Table 1), higher than that from the $Ni(PPh_3)_2Cl_2/ZnI_2$/Zn system. The cyclotrimerization of **1a** and **2** shows great dependence on the solvent used. Of the solvents (THF, toluene, acetonitrile, and dichloromethane) employed (entries 11−13, Table 1), THF gives the highest yield of product **3a**.

Other cyclic enones including 4,4-dimethyl-2-cyclohexen-1-one (**1b**), 2-cyclopenten-1-one (**1c**), and 2-cycloheptен-1-one (**1d**) also successfully undergo [2 + 2 + 2] cycloaddition with **2** in the presence of $Ni(PPh_3)_2I_2$, ZnI_2, and zinc powder in THF to give the corresponding products **3b**−**d** in 32−68% yields (eq 1). Careful examination of the crude products by ^1H NMR showed that cyclohexadiene derivatives **3b′**−**d′** were formed initially in these reactions. However, these diene products were rapidly dehydrogenated during the reaction and purification on the silica gel column. α,β-Unsaturated lactone **5a** (5,6-dihydro-2*H*-pyran-2-one) also undergoes [2 + 2 + 2] cycloaddition smoothly with **2** under similar reaction conditions to give cyclic diene **6** and the corresponding dehydrogenated aromatic product **7** (eq 2). Unlike the

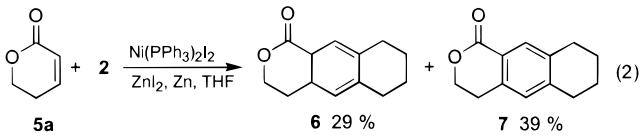
(10) (a) *SRS-A and Leukootrienes*; Piper, P. J., Ed.; Research Studies Press: London, 1981; p 279. (b) *Advances in Prostaglandin, Thromboxane, and Leukotriene Research*, Vol. 9; Samuelsson, B., Paoletti, R., Eds.; Raven Press: New York, 1982; p 341. (c) Clark, D. A.; Marfat, A, *Ann. Rep. Med. Chem.* **1982**, *17*, 291. (d) Borgeat, P.; Sirois, P. *J. Med. Chem.* **1981**, *24*, 121. (e) Kido, Y.; Yamaguchi, M. *J. Org. Chem.* **1998**, *63*, 8086.

Table 3. Nickel-Catalyzed Cocyclotrimerization vs Linear Cotrimerization of Acrylates with Alkynes

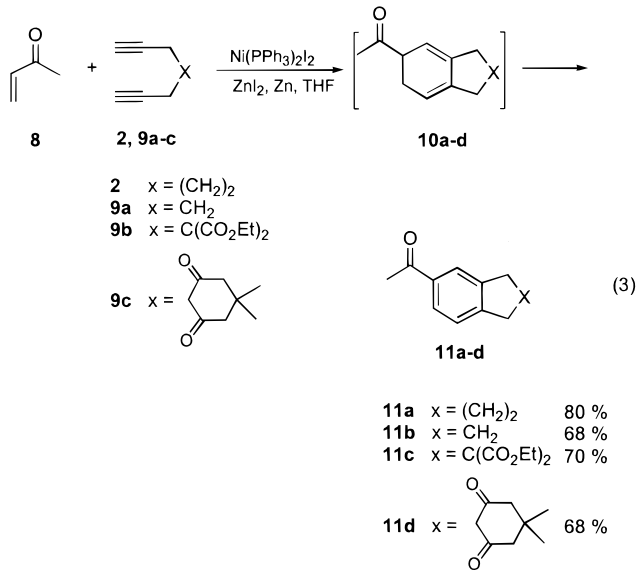
entry	acrylate[a]	alkyne	solvent	catalyst	temp (°C)	time (h)	products (yield, %)
1	**15a**	**16**	toluene	$Ni(PPh_3)_2Cl_2$	60	60	**17a** (82)[c]
2	**15a**	**16**	toluene	$Ni(PPh_3)_2Cl_2$	90	10	**17a** (10)[b]+ **19a** (54)[b]
3	**15a**	**16**	toluene	$Ni(dppe)Cl_2$	60	24	**17a** (6)[b]+ **19a** (56)[b]
4	**15a**	**16**	toluene	$Ni(PPh_3)_2Br_2$	50	24	**17a** (38)[b]+ **19a** (59)[b]
5	**15a**	**16**	toluene	$Ni(PPh_3)_2I_2$	70	24	**17a** (92)[c]
6	**15a**	**16**	CH_2Cl_2	$Ni(PPh_3)_2Cl_2$	25	24	**17a** (22)[b]
7	**15a**	**16**	CH_2Cl_2	$Ni(PPh_3)_2Br_2$	25	24	**17a** (13)[b]+ **19a** (75)[b]
8	**15a**	**16**	CH_2Cl_2	$Ni(PPh_3)_2I_2$	25	24	**17a** (3)[b]
9	**15a**	**12**	toluene	$Ni(PPh_3)_2Cl_2$	90	25	**17b** (30)[b]+ **18b** (16)[b]+ **19b** (49)[b]
10	**15a**	**12**	toluene	$Ni(dppe)Cl_2$	90	25	**17b** (2)[b]+ **18b** (6)[b]+ **19b** (54)[b]
11	**15b**	**16**	toluene	$Ni(PPh_3)_2I_2$	60	21	**17c** (88)[c]
12	**15a**	**2**	THF	$Ni(PPh_3)_2I_2$	62	5	**21** (68)[c]

[a] Reaction conditions: acrylate (2.00 mmol), alkyne (0.720 mmol), nickel catalyst (0.0720 mmol), zinc powder (0.720 mmol), and toluene or CH_2Cl_2 (1.0 mL). [b] Yields are measured on the basis of crude products by an ^1H NMR integration method using DMF as internal standard. [c] Isolated yields.

cyclohexadiene derivatives from cyclic enones, **6** undergoes dehydrogenation slowly and can be isolated. In all these [2 + 2 + 2] cycloaddition reactions, compound **4** was isolated in ca. 10% yield from these reactions.

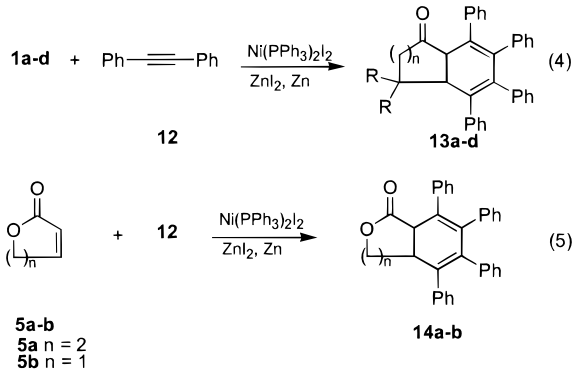


Acyclic enone 3-buten-2-one (**8**) reacts with octa-1,7-diyne and different substituted hepta-1,6-diynes (**9a**−**c**) in the presence of $Ni(PPh_3)_2I_2$, ZnI_2, and Zn powder to give the corresponding cocyclotrimerization−dehydrogenation products **11a**−**d** in 68−80% yields (eq 3). Analysis



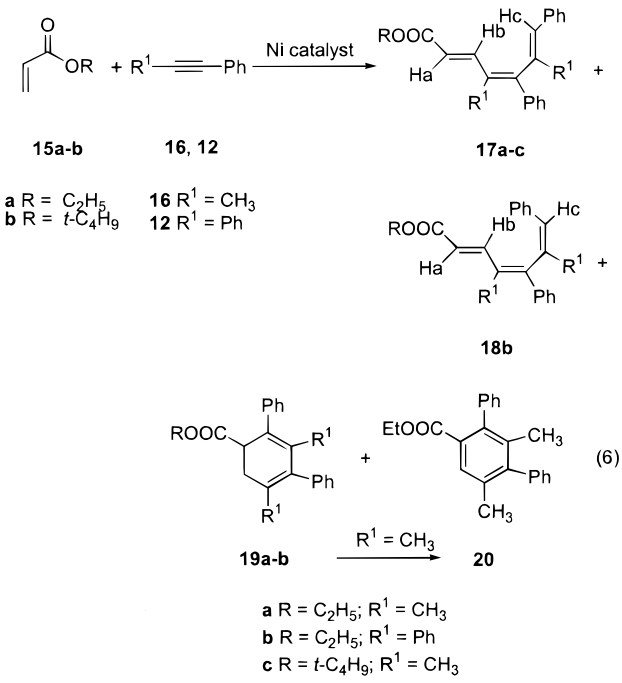
of the crude products from these reactions by ^1H NMR showed the presence of initial [2 + 2 + 2] cycloaddition products **10a**−**d**. These cyclohexadiene derivatives are completely dehydrogenated during silica gel column purification. Cyclic enones **1a**−**d** and lactone **5a** react with hepta-1,6-diyne under similar reaction conditions to give the corresponding [2 + 2 + 2] cycloaddition products in only 15−20% yields. Thus, acyclic enone **8** appears to be more reactive in the [2 + 2 + 2] cycloaddition with hepta-1,6-diynes when compared to cyclic enones and lactones.

The [2 + 2 + 2] cycloaddition is also successfully extended to mono alkynes. For example, the reaction of diphenylacetylene (**12**) with **1a**−**d**, **5a**, and **5b** in the presence of $Ni(PPh_3)_2I_2$ (5 mol %), ZnI_2 (5 mol %), and zinc powder affords the corresponding cyclohexadiene derivatives **13a**−**d**, **14a**, and **14b** in good to excellent yields (Table 2 and eqs 4 and 5). Unlike previous [2 + 2



+ 2] cycloaddition products, **13a**−**d**, **14a**, and **14b** are stable toward dehydrogenation at room temperature. In view of the fact that these cyclohexadiene products consist of enantiomers, it is interesting to see whether catalytic asymmetric [2 + 2 + 2] cocyclotrimerization is possible. Thus, the reaction of **1a** with **12** was carried out in the presence of Ni(*s*-Binap)I_2 (5 mol %), ZnI_2 (5 mol %), and zinc powder in $ClCH_2CH_2Cl$ at 82 °C for 18 h. Product **13a** was isolated in 54% yield. Unfortunately, analysis of the product by a chiral column gives an enantiomeric excess of only 5%.

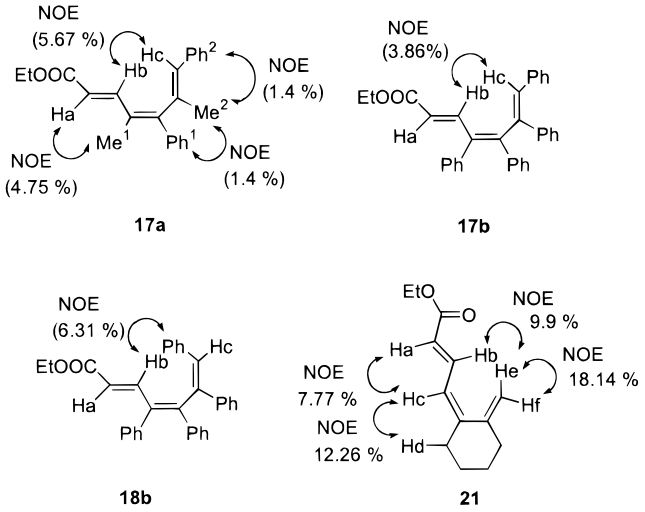
The reaction of acrylates with alkynes catalyzed by nickel complexes gives various products that depend greatly on the reaction conditions. Treatment of ethyl acrylate (**15a**) with 1-phenyl-1-propyne (**16**) in the presence of $Ni(PPh_3)_2Cl_2$ and Zn powder in toluene at 60 °C afforded, instead of the [2 + 2 + 2] cyclotrimerization product, exclusively conjugated triene **17a** in 82% yield (Table 3, entry 1). Similarly, $Ni(PPh_3)_2I_2$/Zn catalyzes the reaction of **15a** with **16** to give triene **17a** in 92% yield and the reaction of *tert*-butyl acrylate (**15b**) with **16** affords triene **17c** in 88% yield (eq 6). Statistically, there are a vast number of possible regio- and stereoisomers for cotrimerization of an α,β-unsaturated carbonyl compound and two similar nonsymmetrical alkyne molecules to give linear trienes. The observation of only one isomer from the reaction of alkyne **16** with acrylate **15a** and **15b**



by using $Ni(PPh_3)_2Cl_2$/Zn or $Ni(PPh_3)_2I_2$/Zn as the catalyst systems suggests that this catalytic reaction is highly stereo- and regioselective. The structures of these trienes were determined on the basis of their MS, ^1H, ^{13}C NMR, NOE, and IR spectral data. The MS data of **17a** displaying a molecular ion at *m*/*z* 332 and a high-resolution mass spectra showing the molecular formula as $C_{23}H_{24}O_2$ firmly support an adduct of two molecules of **16** and a molecule of **15a**. The ^1H NMR spectrum of **17a** displays olefin proton resonances at 5.90 (d, J = 15 Hz) for Ha, 7.90 (d, J = 15 Hz) for Hb, and 6.39 (s) ppm for Hc. The observed coupling constant of 15 Hz between Ha and Hb unequivocally establishes the trans geometry for Ha and Hb. The relative position of methyl and phenyl groups in compound **17a** is determined on the basis of its ^1H NMR NOE difference spectra. Irradiation of the Ha resonance at 5.90 ppm led to a 4.75% enhancement of the Me^1 resonance at 1.68 ppm (Scheme 1). The result shows that in triene **17a** the Me^1 group is near Ha and an alkyne−**16** moiety is connected to the acrylate moiety through the carbon to which Me^1 is attached. Irradiation at the resonance of the Me^2 group produces 1.4% enhancement of the peak intensity of the two phenyl protons. This result suggests that the Me^2 group is located between the two phenyl groups in **17a** and one of the phenyl groups and Me^2 are cis to each other. Finally irradiation of the Hb resonance at 7.90 ppm resulted in 4.75% enhancement of the peak intensity of Hc. These NOE results are wholly in agreement with the proposed trans, cis, and cis structure shown in **17a**. Further evidence for the proposed regiochemistry of **17a** in which a phenyl group is attached to a terminal carbon of the triene is the absence of proton−proton coupling between Hc and Me. A clear coupling between Hc and one methyl group should be observed, if a methyl group is attached to the terminal carbon to which Hc is bonded.

When the reaction of ethyl acrylate with **16** in the presence of $Ni(PPh_3)_2Cl_2$ and Zn powder was carried out at 90 °C in toluene, triene **17a** was obtained only in 10% yield, but the cocyclotrimerization product **19a** was isolated in 54% yield (Table 3, entry 2). Compound **19a**,

Scheme 1



however, undergoes dehydrogenation readily to give the corresponding aromatic compound **20**. The use of nickel complex $Ni(dppe)Cl_2$ as catalyst at 60 °C also produces triene **17a** in 6% yield and cocyclotrimerization product **19a** in 56% yield. On the basis of the above results, it appears that high temperature and bidentate ligand favor the formation of the [2 + 2 + 2] cyclotrimerization product. For the formation of triene, $Ni(PPh_3)_2I_2$ shows the highest selectivity among the nickel complexes used.

Similarly, diphenylacetylene (**12**) reacts with **15a** in the presence of $Ni(PPh_3)_2Cl_2$/Zn or $Ni(dppe)Cl_2$/Zn at 90 °C to afford the corresponding triene and cyclotrimerization products (Table 3, entries 9 and 10). There are two isomers of triene products **17b** and **18b** observed in this reaction. Presumably, triene **17b** that is produced initially isomerizes to **18b** at a terminal carbon−carbon double bond during the reaction. A driving force for this isomerization is likely the release of steric repulsion imparted by the cis geometry of the phenyl groups in **17b**. Like **17a**, triene **17b** shows olefin protons at 5.66 (d, J = 15.6 Hz, Ha), 8.34 (d, J = 15.6 Hz, Hb), and 6.85 (s, Hc) ppm in its ^1H NMR spectrum. Triene **18b** reveals three resonances at 5.43 (d, J = 15 Hz, Hb), 7.62 (d, J = 15 Hz, Ha), and 6.48 (s, Hc) ppm in the ^1H NMR spectrum. The regiochemistry of Ha, Hb, Hc, and phenyl groups of **17b** and **18b** is assigned on the basis of ^1H NMR NOE difference spectra (Scheme 1). Finally, the structure of **17b** was confirmed unambiguously by single-crystal X-ray diffraction analysis (Figure 1). The structures of cyclohexadiene derivatives **19a** and **19b** were also confirmed by spectroscopic methods.

The reaction of ethyl acrylate (**15a**) with octa-1,7-diyne in the presence of $Ni(PPh_3)_2I_2$, ZnI_2, and zinc powder in THF also gives triene derivative **21** in 68% yield (Table 3, entry 12). The structure of **21** is determined on the basis of its spectral data and NOE difference spectra. Terminal alkynes 1-pentyne (**22a**) and 1-hexyne (**22b**) react with **15a** in the presence of $Ni(PPh_3)_2Cl_2$ and Zn powder in CH_2Cl_2 at 25 °C to give a mixture of compounds. The major products in these reactions are trienes **23a** in 62% yield and **23b** in 71% yield, respectively (eq 7). These products were characterized on the basis of ^1H NMR, IR, and GC-MS data. The yields of **23a** and **23b** were measured by an ^1H NMR integration method using an internal standard.

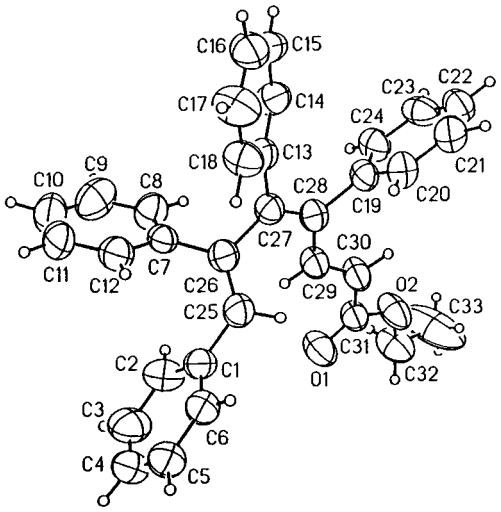
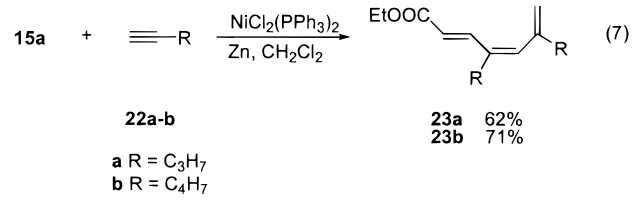
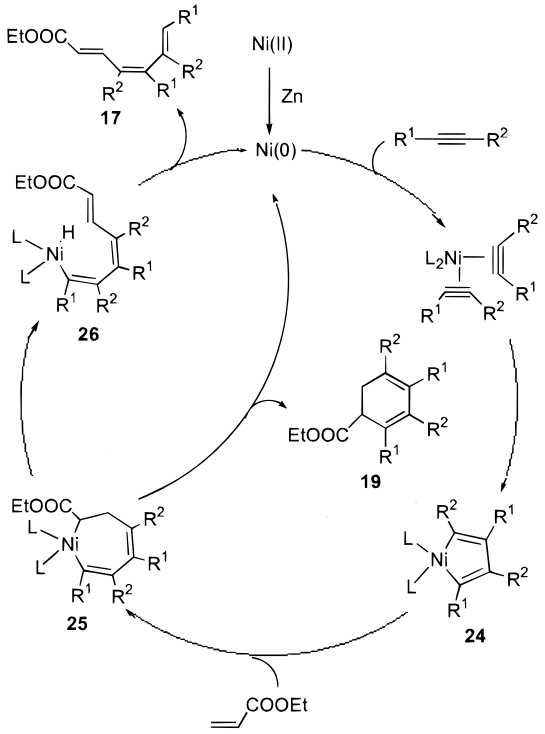


Figure 1. Crystal structure of **17b**.

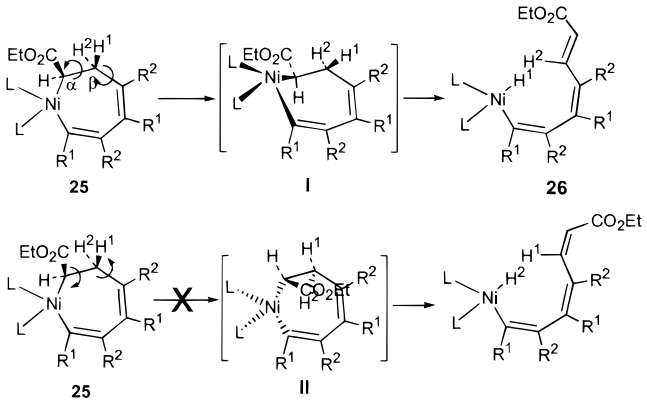


On the basis of the established chemistry of nickel complexes, and the structures of linear cotrimerization and cyclotrimerization products, the mechanism shown in Scheme 2 is proposed to account for the present nickel-catalyzed cocyclotrimerization and linear cotrimerization of an alkene and two alkynes. Reduction of $Ni(PPh_3)_2X_2$ to a Ni(0) species initiates the catalytic reaction. Coordination of two molecules of nonsymmetrical alkynes to the nickel center followed by oxidative cyclometalation produces nickelacyclopentadiene intermediate **24**.[11,12] Coordination of an enone or acrylate molecule and insertion of this molecule into a Ni(II)−carbon bond gives nickelacycloheptadiene intermediate **25**. Reductive elimination of **25** gives a cocyclotrimerization product and regenerates the nickel(0) catalyst. Alternatively, intermediate **25** may undergo β-hydride elimination to give nickel hydride species **26** followed by reductive elimination of **26** to yield a linear triene product and regenerate the nickel catalyst. In view of the high regioselectivity of linear cotrimerization and cyclotrimerization products, preferential formation of the nickelacyclopentadiene intermediate **24** with the R^1-R^2-R^1-R^2 sequence (see Scheme 2) is necessary. The unique stereoselectivity of triene products with each pair of the substituents from the same alkyne cis to each other is attributed to the formation of five-membered ring nickel intermediate **24** during the catalytic reaction. The observed exclusive *E*-selectivity of the acrylate moiety in the linear cotrimerization products indicates that β-hydride elimination of **25** occurs solely at the hydrogen H^1 cis to the ester group (see Scheme 3). This may be explained on the basis

Scheme 2. Mechanism for Cyclotrimerization and Linear Cotrimerization



Scheme 3. Proposed Pathway for β-Hydride Elimination of 25

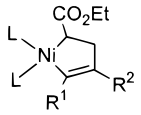


of the requirement that the β-hydrogen for elimination should be syn to the metal center and also the steric effect imparted by the ester group of the acrylate moiety. Elimination of the β-hydrogen H^1 cis to the ester group is expected to proceed via intermediate **I** in which the ester group points out of the nickelacycloheptadiene ring. On the other hand, elimination of the β-hydrogen H^2 trans to the ester group proceeds via intermediate **II** in which the ester group points toward the ring. Due to the repulsion between the ester group and the ring, **II** is expected to be much higher in energy than **I**. Consequently, the major pathway for β-hydride elimination of **25** is that via **I** and the resulting triene product is trans in the acrylate moiety.

An alternative mechanism for the formation of cocyclotrimerization and linear cotrimerization products is coordination of an alkyne and an α,β-unsaturated carbonyl compound to the nickel metal center to produce the five-membered nickelacyclopentene[13] intermediate **24′** followed by insertion of another alkyne into the nickel−carbon bond to which R^1 is attached in **24′** to yield seven-

(11) (a) Eisch, J. J.; Galle, J. E. *J. Organomet. Chem.* **1975**, *96*, C23. (b) Eisch, J. J.; Piotrowski, A. M.; Han, K. I.; Kruger, C.; Tsay, Y. H. *Organometallics* **1985**, *4*, 224. For production of a cobaltacyclopentadiene complex, see: (c) Wakatsuki, Y.; Nomura, O.; Kitaura, K.; Morokuma, K.; Yamazaki, H. *J. Am. Chem. Soc.* **1983**, *105*, 1907.

(12) McAlister, D. R.; Bercaw, J. E.; Bergman, R. G. *J. Am. Chem. Soc.* **1977**, *99*, 1666.



24'

membered ring intermediate **25**. This intermediate then undergoes the same reactions shown in Scheme 2 to give cocyclotrimerization and cotrimerization products. The mechanism cannot be totally ruled out, but it is less likely particularly for the [2 + 2 + 2] cycloaddition of a diyne and an alkene. In this [2 + 2 + 2] cycloaddition, dimerization of the diyne is a competition reaction. The formation of dimer can only be explained on the basis of a nikelacyclopentadiene intermediate.

The fact that the yield of cocyclotrimerization product increases in the presence of Lewis acid suggests a Lewis-assisted insertion of an enone into a carbon−carbon bond of nickelacyclopentadiene intermediate **24**. This observation is similar to that by Ikeda and co-workers.[8] They have shown that cocyclotrimerization is greatly enhanced in the presence of Lewis acid such as $Al(CH_3)_3$ and $ZnCl_2$.

Conclusion

We have demonstrated that nickel systems $Ni(PPh_3)_2X_2$/ZnI_2/Zn effectively catalyze cocyclotrimerization of internal and terminal alkynes and diynes with α,β-unsaturated cyclic and acyclic enones and α,β-unsaturated lactones. This catalytic reaction provides an efficient method for the construction of tricyclic and bicyclic compounds. Previous $Ni(acac)_2/PPh_3/Al(Me)_3$ and $NiCl_2$/$ZnCl_2$/Zn systems reported by Ikeda et al. were used mainly in the synthesis of bicyclic compounds using α,β-unsaturated cyclic and acyclic enones as the alkene substrates. Only one example of a tricyclic compound was demonstrated by using the $NiCl_2/ZnCl_2$/Zn system. The [2 + 2 + 2] cocyclotrimerization of α,β-unsaturated lactones and acrylates with alkynes or diynes is not reported. In addition to [2 + 2 + 2] cocyclotrimerization, the present $Ni(PPh_3)_2X_2$/Zn and $Ni(dppe)Cl_2$/Zn systems also catalyze unprecedented linear cotrimerization of an acrylate with two alkynes to afford highly regio- and stereoselective trienes. Application of these nickel-catalyzed reactions in the synthesis of natural products is in progress.

Experimental Section

All reactions were conducted under a nitrogen atmosphere on a dual-manifold Schlenc line by using purified deoxygenated solvents and standard inert atmosphere techniques, unless otherwise stated. Reagents and chemicals were used as purchased without further purification. Hepta-1,6-diynes **9c**−**d** were prepared by following literature procedures.[14] The catalysts $Ni(PPh_3)_2X_2$[15a] and $Ni(dppe)Cl_2$[15b] were synthesized according to reported procedures.

General Procedure for the Cocyclotrimerization of α,β-Unsaturated Cyclic Enones, Lactones, and 3-Buten-2-one with Diynes. A round-bottom sidearm flask (50 mL) containing $Ni(PPh_3)_2X_2$ (0.0500 mmol), Lewis acid (0.0500 mmol), and zinc powder (0.180 g, 2.75 mmol) was evacuated and purged with nitrogen gas five times. Freshly distilled dry THF (1.0 mL) and an α,β-unsaturated cyclic enone or lactone (1.00 mmol) were added. To the system heated at 60−2 °C with stirring was injected via a syringe pump a solution consisting of diyne (1.5 mmol) and dry THF (2.00 mL) with an injection rate 1.0 mL/h. After addition, the system was further heated at 60−2 °C for 2 h. The solution was stirred in the air for 15 min, filtered through Celite and silica gel, and eluted with dichloromethane. The filtrate was concentrated, and the residue was purified on silica gel column using hexanes−ethyl acetate as eluent to afford the desired products.

A similar procedure was also employed for the reaction of 3-buten-2-one (2.000 mmol) and appropriate diynes (1.000 mmol) to afford **11a**−**c**.

Compounds **11a**−**c** were characterized by comparing their spectral data with those reported earlier.[8b,16] Important spectral data for new compounds **3a**−**d**, **5**, **6**, and **11d** follow.

1,2,3,4,5,6,7,8-Octahydro-1-anthracenone (3a). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.73 (s, 1 H, aromatic), 6.92 (s, 1 H, aromatic), 2.85 (t, *J* = 5.9 Hz, 2 H), 2.75 (br s, 4 H), 2.59 (t, *J* = 6.2 Hz, 2 H), 2.08 (t t, *J* = 6.4 Hz, *J* = 6.3 Hz, 2 H), 1.77 (br s, 4 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 198.25 (s, *C*═O), 143.48 (s), 141.22 (s), 135.50 (s), 130.03 (s), 128.88 (d), 127.34 (d), 39.01 (t), 29.52 (t), 29.10 (t), 28.74 (t), 23.32 (t), 22.87 (t), 22.69 (t). IR (neat): 1680.10 cm^{-1}. HRMS: calcd for $C_{14}H_{16}O$ 200.1202, found 200.1299.

4,4-Dimethyl-1,2,3,4,5,6,7,8-octahydro-1-anthracenone (3b). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.72 (s, 1 H, aromatic), 7.07 (s, 1 H, aromatic), 2.78 (t, *J* = 6.4 Hz, 2 H), 2.75 (t, *J* = 6.8 Hz, 2 H), 2.67 (t, *J* = 6.4 Hz, 2 H, C*H*$_2$−CO), 1.96 (t, *J* = 6.8 Hz, 2 H), 1.77 (br s, 4 H), 1.34 (s, 6 H, C*H*$_3$). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 198.45 (s, *C*═O), 149.25 (s), 143.96 (s), 135.37 (s), 128.85 (s), 127.74 (d), 126.15 (d), 37.28 (t), 35.11 (t), 33.45 (s), 29.96 (t), 29.72 (q), 28.77 (q), 22.99 (t), 22.87 (t). IR (neat): 1682.16 cm^{-1}. HRMS: calcd for $C_{16}H_{20}O$ 228.1515, found 228.1507.

2,3,5,6,7,8-Hexahydro-1*H*-cyclopenta[*b*]naphthalen-1-one (3c). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39 (s, 1 H, aromatic), 7.09 (s, 1 H, aromatic), 2.97 (t, *J* = 5.6 Hz, 2 H), 2.75 (br t, *J* = 5.6 Hz, 4 H), 2.57 (t, *J* = 6.0 Hz, 2 H), 1.73 (q, 4 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 194.46 (s, *C*═O), 152.21 (s), 145.29 (s), 136.74 (s), 126.74 (d), 123.68 (d), 36.46 (t), 30.31 (t), 29.32 (t), 25.24 (t), 22.92 (t), 22.77 (t). IR (neat): 1708.7 cm^{-1}. HRMS: calcd for $C_{13}H_{14}O$ 186.1044, found 186.1056.

2,3,4,6,7,8,9,10-Octahydro-1*H*-cyclohepta[*b*]naphthalen-6-one (3d). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45 (s, 1 H, aromatic), 6.87 (s, 1 H, aromatic), 2.84 (t, *J* = 6.6 Hz, 2 H, *C*O−C*H*$_2$−), 2.74 (s, 4 H), 2.68 (t, *J* = 5.0 Hz, 2 H), 1.84−1.75 (m, 8 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 187.01 (s, *C*═O), 142.01 (s), 138.45 (s), 136.12 (s), 135.51 (s), 130.29 (d), 129.35 (d), 40.87 (d), 32.13 (q), 29.39 (q), 28.79 (q), 25.34 (q), 23.08 (q), 22.93 (q), 20.94 (q). IR (neat): 1672.72 cm^{-1}. HRMS: calcd for $C_{15}H_{18}O$ 214.1358, found 214.1351.

3,4,4a,6,7,8,9,10a-Octahydro-1*H*-benzo[*g*]isochromen-1-one (6). ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.45 (dd, *J* = 2.3 Hz, *J* = 2.3 Hz, 1 H), 5.29 (dd, *J* = 1.9 Hz, *J* = 1.9 Hz, 1 H), 4.38 (m, 1 H), 4.27 (m, 1 H), 3.27 (m, 1 H), 2.79 (m, 1 H), 2.28 (br s, 4 H), 1.89 (m, 2 H), 1.57 (q, *J* = 2.5 Hz, 4 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 173.03 (s, *C*═O), 136.28 (s), 136.20 (s), 121.57 (d), 116.56 (d), 67.96 (t), 40.21 (d), 31.09 (d), 30.57 (t), 30.54 (t), 25.66 (t), 24.07 (t), 23.94 (t). IR (neat): 1727.99 cm^{-1}. HRMS: calcd for $C_{13}H_{16}O_2$ 204.1151, found 204.1137.

3,4,6,7,8,9-Hexahydro-1*H*-benzo[*g*]isochromen-1-one (7). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.78 (s, 1 H, aromatic), 6.92 (s, 1 H, aromatic), 4.47 (t, *J* = 6.0 Hz, 2 H, C*H*$_2$−O−CO), 2.94 (t, *J* = 6.0 Hz, 2 H), 2.77 (s, 4 H), 1.79 (br s, *J* = 3.6 Hz, 4 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 165.56 (s, *C*═O), 143.99 (s)

(13) For production of cobaltacyclopentene complex, see: (a) Wakatsuki, Y.; Aoki, K.; Yamazaki, H. *J. Am. Chem. Soc.* **1974**, *96*, 5284. (b) Wakatsuki, Y.; Aoki, K.; Yamazaki, H. *J. Am. Chem. Soc.* **1979**, *101*, 1123.

(14) Grigg, R.; Scott, R.; Stevenson, P. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1357.

(15) (a) Colquhoun, H. M.; Thompson, D. J.; Twigg, M. V. *Carbonylation*; Plenum Press: 1991. (b) Colquhoun, H. M.; Holton, J.; Thompson, D. J.; Twigg, M. V. *New Pathways For Organic Synthesis-Practical Applications of Transition Metals*; Plenum Press: New York, 1988.

(16) Uhle, F. C.; Krueger, J. E.; Rogers, A. E. *J. Am. Chem. Soc.* **1956**, *78*, 1932.

136.94 (s), 136.31 (s), 130.95 (s), 127.61 (d), 122.47 (s), 67.44 (t), 29.70 (t), 28.91 (t), 27.47 (t), 22.83 (t), 22.70 (t). IR (neat): 1719.55 cm^{-1}. HRMS: calcd $C_{13}H_{14}O_2$ 202.0990, found 202.0990.

The ^1H NMR data of the intermediate dienes **10a**−**d** were also obtained and are listed bellow.

1-(2,3,5,6,7,8-Hexahydro-2-naphthalenyl)-1-ethanone (10a). ^1H NMR (300 MHz, $CDCl_3$): δ 4.46 (br d, J = 3.5 Hz, 1 H), 4.23 (dd, J = 3.2 Hz, J = 8.0 Hz, 1 H), 2.75 (m, 1 H), 2.17 (s, 3 H, CH_3), 2.10 (m, 2 H), 1.82−1.72 (m, 4 H), 1.60 (m, 4 H).

1-(2,3,5,6-Tetrahydro-1*H*-5-indenyl)-1-ethanone (10b). ^1H NMR (400 MHz, $CDCl_3$): δ 4.54 (br d, J = 3.6 Hz, 1 H), 4.27 (dd, J = 3.2 Hz, J = 8.0 Hz, 1 H), 2.87 (m, 1 H), 2.18 (m, 2 H), 2.15 (s, 3 H, CH_3), 2.03−1.96 (m, 4 H), 1.68 (m, 2 H).

Diethyl 5-Acetyl-2,3,5,6-tetrahydro-1*H*-2,2-indenedicarboxylate (10c). ^1H NMR (400 MHz, $CDCl_3$): δ 4.54 (br d, J = 3.6 Hz, 1 H), 4.28 (dd, J = 2.8 Hz, J = 8.0 Hz, 1 H), 4.21 (q, 4 H, CH_2), 2.99 (s, 4 H), 2.88 (m, 1 H), 2.14 (s, 3 H, CH_3), 2.04 (m, 2 H), 1.26 (t, 6 H, CH_3).

5,5-Dimethyl-4′-acetylspiro[hexane-1,3-dione-2,1′-4′,5′-dihydroindane] (10d). ^1H NMR (300 MHz, $CDCl_3$): δ 4.53 (br d, J = 3.5 Hz, 1 H), 4.27 (dd, J = 3.1 Hz, J = 8.1 Hz, 1 H), 3.39 (s, 3 H), 3.35 (s, 1 H), 2.68 (m, 1 H), 2.49 (m, 4 H), 2.23 (s, 3 H, CH_3), 1.95 (m, 2 H), 1.06 (t, 6 H, CH_3).

5,5-Dimethyl-4′-acetylspiro[hexane-1,3-dione-2,1′-indane] (11d). ^1H NMR (300 MHz, $CDCl_3$): δ 6.97 (d, J = 7.9 Hz, 1 H), 6.83 (s, 1 H), 6.82 (d, J = 7.2 Hz, 1 H), 3.33 (s, 4 H), 3.10 (s, 2 H) 2.64 (s, 3 H, CH_3), 1.89 (s, 2 H), 0.99 (s, 6 H, CH_3). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 195.12 (s, *C*═O), 189.66 (s, *C*═O), 139.78 (s), 138.28 (s), 137.87 (s), 129.68 (d), 126.49 (d), 123.99 (d), 71.41 (s), 54.54 (t), 51.43 (t), 44.57 (t), 38.42 (t), 30.55 (s), 28.68 (q), 28.39 (q), 28.33 (q). IR (neat): 1725, 1699.1 cm^{-1}. HRMS: calcd $C_{18}H_{20}O_3$ 284.1441, found 284.1456.

General Procedure for the Cocyclotrimerization of Cyclic Enones and Lactones with Diphenylacetylene. To a round-bottom sidearm flask (50 mL) were added diphenylacetylene (0.356 g, 2.00 mmol), $Ni(PPh_3)_2I_2$ (0.042 g, 0.0500 mmol), ZnI_2 (0.0140 g, 0.0500 mmol), and zinc powder (0.180 g, 2.75 mmol). The system was evacuated and then purged with nitrogen gas five times. To this system were added a freshly distilled appropriate solvent (4.0 mL) and an α,β-unsaturated cyclic enone or lactone (1.00 mmol). The reaction was carried out at a specified temperature and time as shown in Table 2. The reaction mixture was stirred in the air for 15 min at ambient temperature, filtered through Celite and silica gel, and eluted with dichloromethane. The filtrate was concentrated, and the residue was purified on a silica gel column using hexanes−ethyl acetate as eluent to afford the [2 + 2 + 2] products.

Compounds **13a**−**d** and **14a**−**b** were prepared by following this procedure. Important spectral data of these compounds follow.

5,6,7,8-Tetraphenyl-1,2,3,4,4a,8a-hexahydro-1-naphthalenone (13a). ^1H NMR (300 MHz, $CDCl_3$): δ 7.08 (m, 10 H, phenyl), 6.80 (m, 10 H, phenyl), 4.04 (d, J = 6.0 Hz, 1 H, CO−CH), 3.28 (d d d, J = 6.0 Hz, J = 3.3 Hz, J = 3.3 Hz, 1 H), 2.41 (m, 1 H, CH_2), 2.16 (m, 3 H, CH_2), 1.88 (m, 1 H, CH_2), 1.60 (m, 2 H, CH_2). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 212.39 (s, *C*═O), 140.63 (s), 140.15 (s), 139.31 (s), 139.27 (s), 138.27 (s), 137.95 (s), 131.47 (s), 130.99 (d), 130.94 (d), 129.43 (d), 129.13 (d), 127.57 (d), 127.51 (d), 126.94 (d), 126.80 (d), 126.25 (d), 126.24 (d), 125.64 (d), 125.47 (d), 57.88 (d), 45.02 (d), 41.10 (t), 25.51 (t), 25.38 (t). IR (neat): 1706 cm^{-1}. EI-MS *m*/*z* (rel intensity): 452 (M^+, 42.7), 424 (23.1), 395 (21.3), 317 (16.0). HRMS: calcd for $C_{34}H_{28}O$ 452.21141, found 452.2137.

4,4-Dimethyl-5,6,7,8-tetraphenyl-1,2,3,4,4a,8a-hexahydro-1-naphthalenone (13b). ^1H NMR (300 MHz, $CDCl_3$): δ 7.48−6.75 (m, 20 H, phenyl), 4.37 (d, J = 6.4 Hz, 1 H), 3.08 (d, J = 7.8 Hz, 1 H), 2.25 (m, 1 H), 1.95 (m, 1 H), 1.72 (s, 3 H, CH_3), 1.68−1.55 (m, 2 H), 0.64 (s, 3 H, CH_3). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 187.65 (s, *C*═O), 142.66 (s), 140.20 (s), 139.08 (s), 138.90 (s), 131.11 (d), 130.47 (s), 130.36 (d), 129.96 (d), 129.46 (d), 127.36 (d), 126.99 (d), 126.68 (d), 126.38 (d), 126.11 (d), 125.88 (d), 125.51 (d), 57.77 (d), 52.02 (d), 41.98 (t), 37.98 (d), 35.21 (s), 31.38 (q), 22.81 (q). IR (neat): 1709.26 cm^{-1}. HRMS: calcd for $C_{36}H_{32}O$ 480.2445, found 480.2473.

4,5,6,7-Tetraphenyl-2,3,3a,7a-tetrahydro-1*H*-1-indenone (13c). ^1H NMR (400 Hz, $CDCl_3$): δ 7.15−6.97 (m, 10 H, phenyl), 6.96−6.74 (m, 10 H, phenyl), 3.94 (d d, J = 6.4 Hz, J = 7.4 Hz, 1 H), 3.26 (d, J = 8.0 Hz, 1 H), 2.26 (d d, J = 7.2 Hz, J = 17.6 Hz, 1 H), 2.04 (m, 1 H), 1.88 (m, 2 H, CH_2). $^{13}C\{^1H\}$ NMR (75 Hz, $CDCl_3$): δ 181.49 (s, *C*═O), 141.73 (s), 140.17 (s), 140.13 (s), 139.63 (s), 139.59 (s), 132.14 (d), 131.26 (d), 130.85 (d), 129.46 (d), 128.73 (d), 127.77 (d), 127.56 (d), 126.95 (d), 126.72 (d), 126.17 (d), 126.11 (d), 125.59 (d), 125.37 (d), 57.07 (d), 41.93 (d), 35.99 (t), 26.50 (t). IR (KBr): 1735.68 cm^{-1}. HRMS: calcd for $C_{33}H_{26}O$ 438.1983, found 438.1958.

1,2,3,4-Tetraphenyl-5,6,7,8,9,9a-hexahydro-4a*H*-benzo[*a*]cyclohepten-5-one (13d). ^1H NMR (300 Hz, $CDCl_3$): δ 7.19−6.68 (m, 20 H, phenyl), 4.47 (d, J = 5.4 Hz, 1 H, CO−CH), 2.85 (d t, J = 4.6 Hz, J = 10.4 Hz, 1 H), 2.24 (m, 2 H, CH_2), 1.75 (m, 3 H), 1.59 (m, 2 H, CH_2), 1.23 (m, 1 H). $^{13}C\{^1H\}$ NMR (75 Hz, $CDCl_3$): δ 187.23 (s, *C*═O), 141.57 (s), 140.79 (s), 139.92 (s), 139.24 (s), 138.98 (s), 137.93 (s), 136.74 (s), 131.53 (s), 131.00 (d), 130.90 (d), 129.15 (d), 129.03 (d), 127.68 (d), 127.55 (d), 126.95 (d), 126.83 (d), 126.53 (d), 126.28 (d), 125.6 (d), 125.48 (d), 61.90 (d), 43.41 (t), 42.67 (d), 30.68 (t), 26.54 (t), 22.29 (t). IR (neat): 1689.67 cm^{-1}. HRMS: calcd for $C_{35}H_{30}O$ 466.2289, found 466.2286.

5,6,7,8-Tetraphenyl-3,4,4a,8a-tetrahydro-1*H*-1-isochromenone (14a). ^1H NMR (300 MHz, $CDCl_3$): δ 7.21−6.64 (m, 20 H, phenyl), 4.22 (m, 2 H), 3.81 (m, 1 H), 3.73 (d, J = 7.3 Hz, 1 H), 2.19−2.01 (m, 2 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 173.03 (s, *C*═O), 140.96 (s), 139.66 (s), 139.20 (s), 139.09 (s), 138.93 (s), 138.43 (s), 136.74 (s), 132.05 (s), 131.07 (d), 130.81 (d), 129.37 (d), 129.31 (d), 127.68 (d), 127.65 (d), 126.99 (d), 126.83 (d), 126.50 (d), 126.44 (d), 125.81 (d), 126.59 (d), 67.18 (t), 48.14 (d), 35.87 (d), 25.60 (t). IR (neat): 1736.95 cm^{-1}. HRMS: calcd for $C_{33}H_{26}O_2$ 454.1926, found 454.1926.

4,5,6,7-Tetraphenyl-1,3,3a,7a-tetrahydro-1-isobenzofuranone (14b). ^1H NMR (300 MHz, $CDCl_3$): δ 7.27 (m, 3 H, phenyl), 7.13 (m, 6 H, phenyl), 6.93−6.81 (m, 9 H, phenyl), 6.65 (m, 2 H, phenyl), 4.40 (d d, J = 5.1 Hz, J = 8.8 Hz, 1 H), 4.23 (d d, J = 1.2 Hz, J = 8.8 Hz, 1 H), 4.08 (m, 1 H), 3.79(d, J = 8.3 Hz, 1 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 177.67 (s, *C*═O), 140.61 (s), 140.29 (s), 139.33 (s), 139.04 (s), 131.41 (d), 131.09 (d), 130.71 (d), 129.43 (d), 128.79 (d), 128.73 (d), 128.25 (d), 127.72 (d), 127.05 (d), 126.89 (d), 126.75 (d), 126.61 (d), 126.54 (d), 125.91 (d), 125.70 (d), 125.15 (d), 71.37 (t), 47.03 (d), 42.69 (d). IR (KBr) 1767.86 (C═O), 1597.85 cm^{-1}. HRMS: calcd for $C_{32}H_{24}O_2$ 440.1776, found 440.1763.

General Procedure for the Reaction of Acrylates with 1-Phenyl-1-propyne. A round-bottom sidearm flask (50 mL) was charged with $Ni(PPh_3)_2X_2$ or $Ni(dppe)Cl_2$ (0.0720 mmol) and zinc powder (0.0475 g, 0.720 mmol). The system was evacuated and purged with nitrogen gas five times. Freshly distilled toluene or CH_2Cl_2 (1.0 mL), acrylates (2.00 mmol) were added, and the solution was stirred at ambient temperature for 10 min to dissolve the catalyst completely. To this system was added 1-phenyl-1-propyne (0.090 mL, 0.720 mmol), and the reaction was carried out at a specified temperature and time as shown in Table 3. The reaction mixture was stirred in the air for 15 min at ambient temperature, filtered through Celite and silica gel, and eluted with dichloromethane. The filtrate was concentrated, and the residue was separated on a silica gel column using hexane−dichloromethane (2:1) as eluent to afford the desired products. Spectral data for compounds **17a** and **17c** are listed below, while the yields of these products are shown in Table 3.

Compounds **17b**, **18b**, and **19b** were also prepared from the reaction of ethyl acrylate (0.20 mL, 2.00 mmol) and diphenylacetylene (0.0891 g, 0.5000 mmol) in the presence of $Ni(PPh_3)_2Cl_2$ (or $Ni(dppe)Cl_2$) (0.0500 mmol), Zn (0.1800 g, 2.750 mmol), and PPh_3 (0.1574 g, 0.6000 mmol) in toluene (2.0 mL) at 90 °C for 25 h by following a procedure similar to that described above. Important spectral data of these products follow.

Ethyl (2*E*,4*Z*,6*E*)-4,6-Dimethyl-5,7-diphenyl-2,4,6-heptatrienoate (17a). ^1H NMR (400 MHz, $CDCl_3$): δ 7.90 (d, J

= 15 Hz, 1 H), 7.21−7.28 (m, 5 H), 7.12−7.20 (m, 5 H), 6.39 (s, 1 H), 5.90 (d, J = 15 Hz, 1 H), 4.10 (q, J = 6.8 Hz, 2 H), 1.68 (s, 3 H), 1.59 (s, 3 H), 1.17 (t, J = 6.8 Hz, 3 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 167.53, 153.60, 145.66, 145.66, 139.54, 137.64, 137.24, 132.56, 129.23, 128.98, 128.74, 128.07, 128.03, 127.54, 126.70, 117.61, 59.99, 16.18, 14.17; IR (neat): 1712 cm^{-1}. EI-MS m/z (rel intensity): 332 (M^+, 86.7), 259 (M − $COOEt^+$, 100). HRMS: calcd for $C_{23}H_{24}O_2$ 332.1777, found 332.1782.

Ethyl (2*E*,4*E*,6*E*)-4,5,6,7-Tetraphenyl-2,4,6-heptatrienoate (17b). Mp: 150−152 °C. ^1H NMR (300 MHz, $CDCl_3$): δ 8.34 (d, J = 15.6 Hz, 1 H), 7.12−7.25 (m, 4 H), 7.02−7.12 (m, 3 H), 6.92−6.99 (m, 3 H), 6.85 (s, 1 H), 5.66 (d, J = 15.6 Hz, 1 H), 4.11 (q, J = 7.0 Hz, 2 H), 1.17 (t, J = 7.1 Hz, 3 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 167.46, 146.20, 136.56, 134.52, 131.11, 130.49, 129.69, 129.59, 128.22, 128.08, 128.04, 127.35, 127.05, 127.00, 121.80, 60.12, 14.14. IR (neat): 1708 cm^{-1}. EI-MS m/z (rel intensity): 278 (M^+, 42.7), 205 (M − $COOEt^+$, 100). HRMS: calcd for $C_{19}H_{18}O_2$ 278.1307, found 278.1294.

***tert*-Butyl (2*E*,4*Z*,6*E*)-4,6-Dimethyl-5,7-diphenyl-2,4,6-heptatrienoate (17c).** ^1H NMR (400 MHz, $CDCl_3$): δ 7.94 (d, J = 16 Hz, 1 H), 7.21−7.37 (m, 10 H), 6.48 (s, 1 H), 5.92 (d, J = 15.2 Hz, 1 H), 1.85 (s, 3 H), 1.77 (s, 3 H), 1.46 (s, 6 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 166.98, 153.08, 144.74, 139.81, 137.84, 137.43, 132.38, 129.36, 129.10, 128.94, 128.10, 127.53, 126.73, 119.73, 79.92, 28.20, 18.15, 16.32. IR (neat): 1704 cm^{-1}. EI-MS m/z (rel intensity): 360 (M^+, 0.3), 303 (M − $C(CH_3)_3^+$, 24), 259 (44). HRMS: calcd for $C_{25}H_{18}O_2$ 360.2090, found 360.2086.

Ethyl 3,4,5,6-Tetraphenyl-2,4-cyclohexadiene-1-carboxylate (19b). ^1H NMR (300 MHz, $CDCl_3$): δ 6.97−7.07 (m, 5 H), 6.91−6.94 (m, 3 H), 6.77−6.78 (m, 6 H), 6.69−6.71 (m, 3 H), 6.62−6.65 (m, 3 H), 4.10 (q, J = 7.1 Hz, 2 H), 3.59 (t, J = 5.9 Hz, 1 H), 3.18 (t, J = 4.6 Hz, 2 H), 1.12 (t, J = 7.1 Hz, 3H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 174.00, 142.22, 141.55, 139.39, 139.26, 137.22, 134.10, 132.99, 131.05, 130.94, 130.00, 129.15, 128.47, 127.62, 127.53, 126.96, 126.93, 126.12, 126.09, 125.56, 125.57, 60.90, 46.78, 34.30, 14.23. IR (neat): 1721 cm^{-1}. EI-MS m/z (rel intensity): 456 (M^+, 76), 383 (M − $COOEt^+$, 100). HRMS: calcd for $C_{33}H_{28}O_2$ 456.2090, found 456.2075.

Ethyl 2,4-Diphenyl-3,5-dimethylbenzoate (20). ^1H NMR (400 MHz, $CDCl_3$): δ 7.59 (s, 1 H, aromatic), 7.33−7.24 (m, 10 H, phenyl), 3.99 (q, 2 H, CH_2), 2.07 (s, 3 H, CH_3), 1.75 (s, 3 H, CH_3), 0.92 (t, 3 H, CH_3). GCMS: 330 (M^+).

Compound **21** was prepared from the reaction of ethyl acrylate (0.20 mL, 2.00 mmol) and 1,7-octadiyne (0.130 mL, 1.00 mmol) in the presence of $Ni(PPh_3)_2I_2$ (0.0500 mmol), Zn (0.180 g, 2.75 mmol), and ZnI_2 (0.0140 g, 0.0500 mmol) in THF (2.0 mL) at 60 °C for 5 h by following a procedure similar to that described above. Important spectral data of this product follow.

Ethyl (2*E*,4*Z*)-4-(2-Methylenecyclohexylidene)-2-butenoate (21). ^1H NMR (300 MHz, $CDCl_3$): δ 7.66 (d d, J = 11.3 Hz, J = 15.3 Hz, 1 H), 5.97 (d, J = 11.37 Hz, 1 H), 5.81 (d, J = 15.4 Hz, 1 H), 5.05 (d, J = 1.9 Hz, 1 H), 4.77 (d, J = 1.05 Hz, 1 H), 4.15 (q, J = 7.1 Hz, 2 H), 2.29 (m, 2 H, CH_2), 2.24 (m, 2 H, CH_2), 1.68 (m, 4 H, CH_2), 1.26 (t, J = 4.6 Hz, 3 H, CH_3). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 167.63, 153.23, 146.04,142.06, 121.82, 119.52, 113.49, 60.05, 37.98, 36.55, 27.61, 27.51, 14.31. IR (neat): 1713, 1625 cm^{-1}. HRMS (FAB, M + 1): calcd for $C_{13}H_{19}O_2$ 207.1385, found 207.1392.

Synthesis of Ethyl (2*E*,4*Z*)-4,6-Dipropyl-2,4,6-heptatrienoate (23a) from Ethyl Acrylate and 1-Pentyne. A 50 mL round-bottom sidearm flask was charged with $Ni(PPh_3)_2Cl_2$ (0.0653 g, 0.1000 mmol) and zinc powder (0.0983 g, 1.500 mmol). The system was evacuated and purged with nitrogen gas five times. Freshly distilled CH_2Cl_2 (1.0 mL) and 1-pentyne (0.30 mL, 3.00 mmol) were added, and the solution was stirred at ambient temperature for 10 min to dissolve the catalyst completely. To this reaction mixture was added ethyl acrylate (0.20 mL, 2.00 mmol), and the mixture was stirred at room temperature for 12 h. The reaction mixture was stirred in the air for 15 min at ambient temperature, filtered through Celite and silica gel, and eluted with dichloromethane. The filtrate was concentrated, and the resultant residue was purified on a silica gel column using hexane−dichloromethane (2:1) as eluent. A mixture of isomers was obtained in 76% yield (0.2693 g). The yield of desired product **23a** was measured as 62% by an ^1H NMR integration method using DMF as the internal standard. Spectral data for **23a** follow. ^1H NMR (400 MHz, $CDCl_3$): δ 7.74 (d, J = 15.2 Hz, 1 H), 6.04 (s, 1 H), 5.88 (d, J = 16 Hz, 1 H), 5.05 (s, 1 H), 4.77 (s, 1 H), 4.12 (q, J = 4.4 Hz, 2 H), 2.01−2.18 (m, 4 H), 1.34−1.44 (m, 4 H), 1.21 (t, J = 5.2 Hz, 3 H), 0.83−0.85 (m, 6 H). IR (neat): 1718, 1623 cm^{-1}. EI-MS m/z (rel intensity): 236 (M^+, 15), 207 (M − Et^+, 12). HRMS: calcd for $C_{15}H_{24}O_2$ 236.1777, found 236.1771.

By following a procedure similar to that described above, **23b** was obtained from the reaction of 1-hexyne (0.35 mL, 3.00 mmol) and ethyl acrylate (0.20 mL, 2.00 mmol) in the presence of $Ni(PPh_3)_2Cl_2$ (0.0653 g, 0.1000 mmol) and Zn (0.0987 g, 1.500 mmol) in CH_2Cl_2 (1.00 mL) at room temperature for 12 h. A product mixture was obtained from the reaction which we were unable to separate. The yield of **23b** (71%) was measured by an ^1H NMR integration method with DMF as the internal standard. Important spectral data of **23b** follow.

Ethyl (2*E*,4*Z*)-4,6-Dibutyl-2,4,6-heptatrienoate (23b). ^1H NMR (300 MHz, $CDCl_3$): δ 7.82 (d, J = 16 Hz, 1 H), 6.12 (s, 1 H), 5.96 (d, J = 16 Hz, 1 H), 5.13 (s, 1 H), 4.84 (s, 1 H), 4.21 (q, J = 7.1 Hz, 2 H), 2.09−2.28 (m, 4 H), 1.28−1.38 (m, 8 H), 0.87−0.94 (m, 5 H). IR (neat): 1715, 1623 cm^{-1}. EI-MS m/z (rel intensity): 264 (M^+, 23). HRMS: calcd for $C_{17}H_{28}O_2$ 264.2090, found 264.2086.

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Supporting Information Available: ^1H NMR, NOE, and ^{13}C NMR spectra of **3a**−**d**, **5**, **6**, **10d**, **13a**−**d**, **14a**,**b**, **17a**−**c**, **19b**, and **21**, tables of crystal data and thermal parameters, and ORTEP drawing of compound **17b**. This material is available free of charge via the Internet at http://pubs.acs.org.

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