27.96; GC-MS (70 eV), M^+, 136 (50), 108 (100), 80 (50), 79 (58), 77 (25), 66 (20), 52 (90), 39 (58), 27 (65). Anal. Calcd for $C_8H_8O_2$: C, 70.59; H, 5.88. Found: C, 70.38; H, 5.83.

17e: mp 61-2 °C (ether-pentane) (lit.[20] mp 64.5-65 °C); IR 1735, 1715, 1645 cm^{-1}; ^1H NMR δ 2.1-2.7 (m, 4 H, 2 CH_2C=), 2.55-2.05 (m, 4 H, 2 CH_2) 6.1 (d, J = 9 Hz, 1 H, =CHC=O), 7.1 (d, J = 9 Hz, 1 H, CH=C); ^{13}C NMR δ 162.7, 159.77, 146.66, 113.01, 112.54, 27.38, 25.35, 21.96, 21.57; GC-MS (70 eV), M^+, 150 (38), 122 (80), 94 (100), 79 (25), 66 (35), 52 (32), 39 (65), 27 (45), 18 (20). Anal. Calcd for $C_9H_{10}O_2$: C, 72.00; H, 6.67. Found: C, 71.83; H, 6.62.

Reaction of 8b with Polyphosphoric Acid (PPA). Preparation of the α-Pyrone, 17b. A mixture of freshly prepared PPA (27.6 g) and **8b** (1.4 g, 10 mmol) was stirred at 90 °C for 22 h. The reaction mixture was cooled to 25 °C, and ice-water (30 mL) was added. The aqueous layer was saturated with NaCl and extracted with CH_2Cl_2 (3 × 100 mL). The CH_2Cl_2 layer was washed and dried as before. Removal of solvent provided a residue (1.26 g), which was analyzed (^1H NMR) to contain **17b** (~31%) and the starting **8b** (69%). The residue was purified by column chromatography using hexane-chloroform (4:1) as eluent to yield **17b** (0.38 g, 25%), which solidified after several days in the refrigerator. Crystallization from petroleum ether (40-60 °C) yielded a white solid: mp 61-2 °C (lit.[21] mp 62-3 °C); IR, 1780, 1720, 1640 cm^{-1}; ^1H NMR δ 2.25 (s, 3 H, CH_3), 2.0 (d, J = 2 Hz, 3 H, 3 H, CH_3) 6.1 (dd, J = 11, 2 Hz, 1 H, =CHC=O), 7.18 (d, J = 11 Hz, CH=C).

Acknowledgment. We thank IEL Limited for financial support and Dr. P. Ghosh for many helpful discussions. We also thank one of the referees for his suggestions concerning the mechanism of the formation of γ-lactones.

Registry No. **6a**, 3128-06-1; **6b**, 6818-07-1; **6c**, 70223-33-5; **6d**, 114942-61-9; **6e**, 118890-80-5; **6f**, 118890-81-6; **6g**, 118890-82-7; **7a**, 3740-59-8; **7b**, 4054-96-0; **7c**, 70174-49-1; **7d**, 5587-71-3; **7e**, 700-82-3; **7f**, 72925-36-1; **7g**, 63665-45-2; **8a**, 69308-41-4; **8b**, 118890-83-8; **8c**, 119006-94-9; **8d**, 118890-84-9; **8e**, 118890-85-0; **8f**, 118890-86-1; **8g**, 118890-87-2; **9b**, 118890-88-3; **10**, 118890-89-4; **11**, 118890-90-7; **17b**, 4209-44-3; **17d**, 5650-69-1; **17e**, 16326-65-1.

(20) Dreiding, A. S.; Tomasewski, A. J. *J. Am. Chem. Soc.* **1954**, *76*, 6388.

(21) Reference 15, p 2214.

Alkylation of Allylic Derivatives. 14.[1] Relationship of Double-Bond Configuration between Reactant and Product for Cross-Coupling Reactions of *Z*-Allylic Carboxylates with Organocopper Reagents

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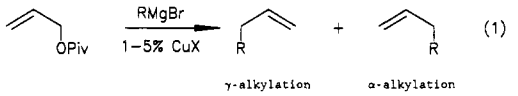
Cross-coupling reactions of alkylcuprates (sp^3 reagents) with allylic carboxylates can result in loss of double-bond configuration in the α-alkylation product. Loss of configuration occurs during the reaction, which shows that an intermediate is involved in which the double bond is temporarily relocated. With phenyl- and vinylcuprates (sp^2 reagents) the original double-bond configuration is fully preserved in all cases. This shows that the original double bond is partly retained throughout the reaction. Evidently with sp^2 reagents, oxidative addition leads directly to a π-allylcopper(III) complex (**12**).

In earlier work[1] we presented evidence that cross-coupling reactions of allylic carboxylates with organocopper reagents involve oxidative addition with allylic rearrangement to give a (γ-σ-allyl)copper(III) complex (**1**) as illustrated in Scheme I. The most important evidence in this connection is (a) γ-alkylation inevitably predominates in unbiased systems,[2] and (b) the original double-bond configuration becomes vulnerable during the reaction.[3] For example, regioselective[4] cross-coupling of *cis*-cinnamyl acetate (*cis*-**2**-OAc) with $LiCuMe_2$ gives mainly the α-alkylation product, 1-phenylpropene, with substantial loss of double-bond configuration.[3] As shown in Scheme I, α-coupling involves the temporary relocation of the double bond. Rotation of the C_β-C_γ single bond in **1** prior to allylic rearrangement to the (α-σ-allyl)copper(III) complex (**3**) results in loss of configuration.

Our original studies[3] involved the so-called stoichiometric method in which an allylic carboxylate reacts with an excess of preformed organocuprate. More recently we have found that copper(I)-catalyzed cross-coupling reactions of Grignard reagents and allylic carboxylates (eq 1)



(1)

offer important advantages over the stoichiometric method.[5] Pivalate esters are generally used in the catalytic procedures to avoid carbonyl attack by the Grignard reagent.[5]

From a comparison of stereo- and regiochemistry for the two processes, we concluded that organocuprates (e.g. $R_2CuMgBr$ for RMgBr containing 1% CuCl) are generated in the catalytic process and that the two methods are mechanistically similar.[5b]

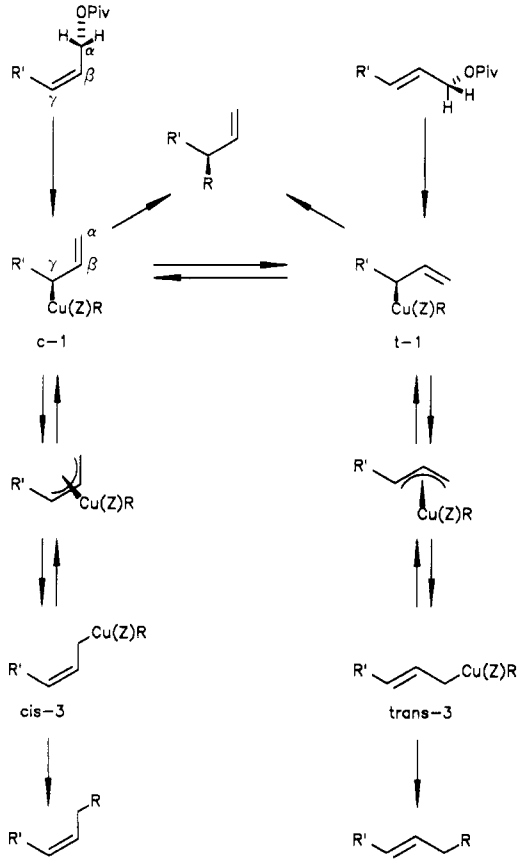
We now have investigated the alkylation of *cis*-cinnamyl (*cis*-**2**-OPiv), *cis*-crotyl (*cis*-**4**-OPiv), and (*Z*,*E*)-3,5-heptadienyl pivalates ((*Z*,*E*)-**5**-OPiv) by the catalytic method (*n*-BuMgBr containing 1% CuCl) to determine if the or-

(1) Previous paper in this series: Underiner, T. L.; Goering, H. L. *J. Org. Chem.* **1988**, *53*, 1140.
(2) Goering, H. L.; Singleton, V. D., Jr. *J. Org. Chem.* **1983**, *48*, 1531.
(3) Goering, H. L; Kantner, S. S. *J. Org. Chem.* **1983**, 48, 721.
(4) The terms regiospecific and regioselective are used as defined in footnote 3 of ref 2.

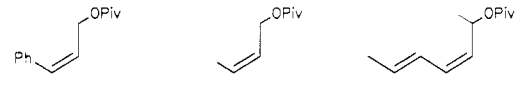
(5) (a) Tseng, C. C.; Yen, S.; Goering, H. L. *J. Org. Chem.* **1986**, *51*, 2892. (b) Tseng, C. C.; Paisley, S. D.; Goering, H. L. *Ibid.* **1986**, *51*, 2884.

0022-3263/89/1954-2369$01.50/0

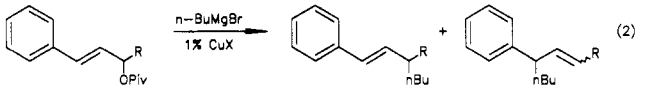
Scheme I. Mechanism for Cross Coupling Allylic Carboxylates with Alkylcuprates



iginal double-bond configuration is preserved in the α-alkylation product.



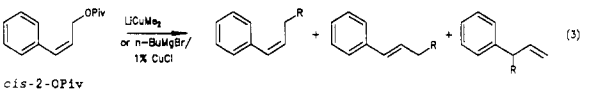
In earlier work[5b] we found that the regiochemistry of cross-coupling reactions of alkyl Grignard reagents depends on the cuprous salt used for catalyst. Cross-coupling *trans*-α-methyl-γ-phenylallyl pivalate (*trans*-**6**-OPiv) with *n*-BuMgBr is highly regiospecific with catalytic CuCN and gives >97% γ-alkylation; with catalytic CuCl the reaction regioselectively leads to 89% α-alkylation (eq 2). We now



		α-alkylation	γ-alkylation
trans-6-OPiv (R = Me)			
	X = CN	<3%	>97%
	X = Cl	89%	11%
trans-2-OPiv (R = H)			
	X = CN	2%	98%
	X = Cl	94%	6%

report similar results for the *trans*-cinnamyl system. As shown by eq 2, alkylation of *trans*-**2**-OPiv in ether with 2 equiv of *n*-BuMgBr in the presence of 1% CuCN regiospecifically gives 98% γ-alkylation; with 1% CuCl, the reaction gives 94% α-alkylation. Clearly CuCl is the catalyst of choice for the present study because the α-alkylation product is the only one of interest.

Results for alkylation of *cis*-**2**-OPiv in ether with 2 equiv of *n*-BuMgBr containing 1% CuCl are presented in eq 3. The results of key experiments of an earlier investigation[3] of the stoichiometric alkylation with $LiCuMe_2$ are included



cis-2-OPiv				
n-BuMgBr/1% CuCl[a]	0°C	93.9	4.4	1.7
	-78°C	52.1	38.6	9.2
$LiCuMe_2$	0°C	57.0	42.0	1.0
	-78°C	0.4	99.5	0.5

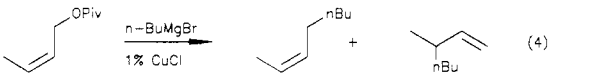
[a] *cis*-2-OPiv was contaminated with 1.8% *trans*-2-OPiv.

for comparison. In these experiments, the isomeric purity of the pivalate was greater than 98%; capillary GC and ^1H NMR indicated 1.8% of *trans*-**2**-OPiv as the only impurity. Product ratios were determined by capillary GC, and homogeneous samples of all alkylation products were isolated by preparative GC and fully characterized by comparison with authentic samples.

The results under eq 3 indicate that the reaction pathways are similar for the catalytic and stoichiometric processes and thus support the view that with *n*-BuMgBr containing 1% CuCl, a dialkylcuprate, $(n\text{-Bu})_2CuMgBr$, is generated in a catalytic cycle.[5b] Evidently in each case, the mechanistic pathway is that outlined in Scheme I and loss of double-bond configuration results from the c-1 → t-1 transformation.

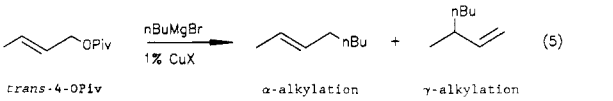
That loss of configuration occurs during, and not prior, to reaction was established by monitoring the unreacted *cis*-**2**-OPiv during the reaction and noting that *trans*-**2**-OPiv is not formed. Since *trans*-**2**-OPiv reacts only slightly faster than *cis*-**2**-OPiv,[3] cis to trans isomerization would result in accumulation of *trans*-**2**-OPiv. In fact, the trace amount of *trans*-**2**-OPiv initially present (1.8%) decreased during the reaction; thus, there is no isomerization prior to alkylation.

Results for cross coupling *cis*-crotyl pivalate (*cis*-**4**-OPiv) with 1.1 equiv of *n*-BuMgBr/1% CuCl in ether at −20 °C are shown in eq 4. In this case, alkylation occurs regioselectively and affords predominantly the α-substitution product. The isomeric purity of *cis*-**4**-OPiv was greater than 99%; ^1H NMR analysis showed 0.9% *trans*-**4**-OPiv as the only contaminant.



cis-4-OPiv	α-alkylation	γ-alkylation
	91%	9%

The regiochemistry for the copper(I)-catalyzed alkylation of *trans*-crotyl pivalate (*trans*-**4**-OPiv) with *n*-BuMgBr was also investigated. As in the cinnamyl and other allylic systems, regiochemistry depends on the type of cuprous salt used as the catalyst.[5] As shown in eq 5, cross-coupling *trans*-**4**-OPiv with *n*-BuMgBr/1% CuCl is regioselective and affords 98% α-alkylation; with 1% CuCN the reaction is highly regiospecific and gives 99% of the γ-alkylation product (eq 5).



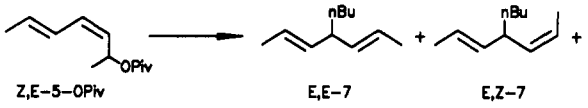
trans-4-OPiv	α-alkylation	γ-alkylation
X = Cl	98%	2%
X = CN	1%	99%

In contrast to the *cis*-cinnamyl system, no detectable loss of double-bond configuration was observed for α-alkylation of *cis*-**4**-OPiv. Comparison of results for the two systems is instructive. As shown in Scheme I, loss of double-bond configuration results from rotation about the temporary C_γ–C_β single bond. In the *cis*-cinnamyl system (R′ = Ph) bond rotation occurs in competition with the c-1 → cis-**3**

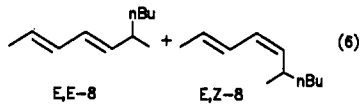
transformation, and partial loss of the original double-bond configuration results. In the *cis*-crotyl system (R′ = Me) bond rotation (c-1 → t-1) relative to the c-1 → cis-3 transformation is slow and loss of double-bond configuration is not detected. Evidently the difference results from larger steric congestion in the initially formed c-1 in the cinnamyl system. Put another way, the driving force for bond rotation is larger in the cinnamyl system than in the crotyl system. Molecular mechanics calculations (MM2)[6] also indicate a lower barrier to rotation about the C_γ–C_β bond (c-1 → t-1 transformation) for the cinnamyl system verses the crotyl system.

The results for the *cis*-crotyl system are similar to those reported earlier[7] for alkylation of *cis*- and *trans*-crotyl acetate (4-OAc) with *n*-BuMgBr/2.5% CuI in THF–ether at −78 °C. Under these conditions, only α-alkylation was observed, and double-bond configuration was preserved with both isomers.[7]

Results for cross-coupling (*Z*,*E*)-3,5-heptadien-2-yl pivalate ((*Z*,*E*)-**5**-OPiv) in ether with a 2-fold excess of cuprate (at −20 °C) or Grignard reagent containing a catalytic amount of cuprous salt (at room temperature) are shown under eq 6. Capillary GC was usually effective for



	E,E-7	E,Z-7
$LiCuBu_2$	3.3%	0%
n-BuMgI/5% CuI	48.9%	9.2%
LiCu(CN)Bu	88.2%	5.5%
n-BuMgI/1% CuCN	91.7%	8.3%



(6)

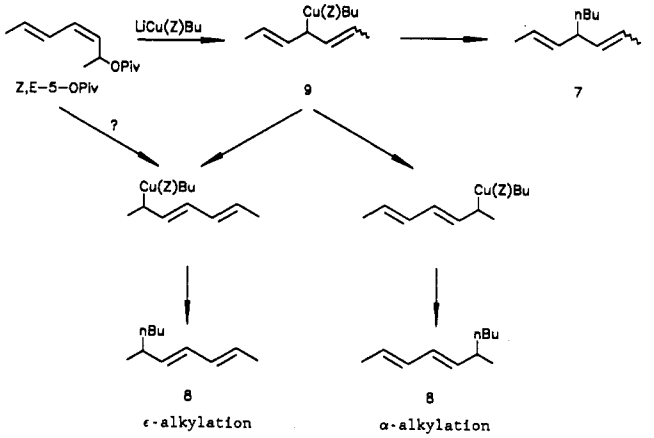
	E,E-8	E,Z-8
$LiCuBu_2$	87.2%	9.5%
n-BuMgI/5% CuI	28.0%	13.9%
LiCu(CN)Bu	4.0%	0%
n-BuMgI/1% CuCN	0%	0%

determining product distributions, but baseline resolution of (*E*,*Z*)-**7** and (*E*,*E*)-**7** was unobtainable; however, the ratio could be determined, if necessary, by ^{1}H NMR integration. Products were isolated by preparative GC and fully characterized spectrally.

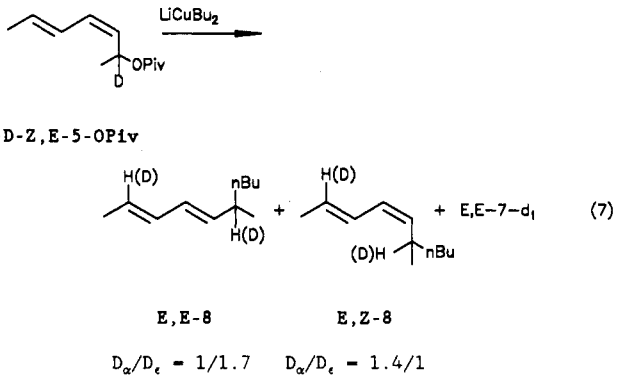
As shown in eq 6, the degree of regiospecificity (γ-alkylation to give **7**) associated with each of the butylcopper reagents increases in the order $LiCuBu_2$ < *n*-BuMgI/5% CuI < LiCu(CN)Bu < *n*-BuMgI/1% CuCN. This is similar to the order observed for other allylic systems.[5] Cross-coupling (*Z*,*E*)-**5**-OPiv with LiCu(CN)Bu or *n*-BuMgI/1% CuCN is highly regiospecific and gives 96% and 100% γ-alkylation even though the system is biased in favor of the conjugated α- or ε-alkylation product. Alkylation with $LiCuBu_2$ is regioselective and affords predominantly the conjugated product **8**. This was the reagent of choice for the present investigation since the α-alkylation product is the one of interest.

In this system the conjugated product (**8**) can result from either α- or ε-alkylation. In the latter case the double bonds are relocated. Thus, to determine if the original double-bond configuration is lost in the α-alkylation product, it is necessary to know if (*E*,*E*)-**8** results, at least in part, from α-alkylation.

Scheme II. Pathways for Formation of (*E*,*E*)-8 from Alkylation of (*Z*,*E*)-5-OPiv with Butylcopper Reagents



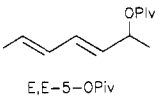
α-Deuterated **5**-OPiv was used to distinguish between α- and ε-alkylation. The isomeric products resulting from alkylation of α-D-(*Z*,*E*)-**5**-OPiv with $LiCuBu_2$ (eq 7) were separated by preparative GC, and the two isomers of **8** were examined by ^{1}H NMR. The deuterium distributions



D_α/D_ϵ = 1/1.7 D_α/D_ϵ = 1.4/1

were determined by integration of appropriate vinyl and allylic hydrogen signals. Results are presented in eq 7; the D_α/D_ϵ ratios correspond to the ratio of α- to ε-alkylation. These results show that a substantial fraction of (*E*,*E*)-**8** results from α-alkylation. Thus, the original double-bond configuration is partially lost, which indicates the intermediacy of a (γ-σ-allyl)copper(III) complex (**9**) as illustrated in Scheme II.

Control experiments showed that the rate of cross-coupling (*Z*,*E*)-**5**-OPiv with $LiCuBu_2$ is comparable to that of (*E*,*E*)-3,5-heptadien-2-yl pivalate ((*E*,*E*)-**5**-OPiv);[8] if cis to trans isomerization preceded alkylation, (*E*,*E*)-**5**-OPiv would accumulate. Incomplete reaction (~50%) of (*Z*,*E*)-**5**-OPiv with $LiCuBu_2$ gave back only (*Z*,*E*)-**5**-OPiv; thus, (*Z*,*E*)-**5**-OPiv does not isomerize to (*E*,*E*)-**5**-OPiv prior to alkylation.



In other work[5b] we reported that cross-coupling α-deuterio-2-cyclohexenyl mesitoate (α-D-**10**-OMes) with PhMgBr or propen-2-ylmagnesium bromide in the presence of 3% CuCN proceeds without regiospecificity (equilibrium amounts[9] of α- and γ-coupling is observed).

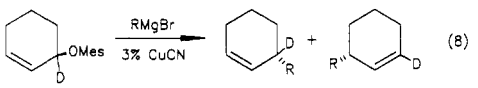
(6) The MACROMODEL version of Alinger's molecular mechanics (MM2) program was used. An isopropyl group was substituted for the Cu(Z)R group.

(7) Fouquet, G.; Schlosser, M. *Angew. Chem. Int. Ed.* **1974**, *13*, 82.

(8) Gajewski, J. J.; Jurayj, J.; Kimbrough, D. R.; Gande, M. E.; Ganem, B.; Carpenter, B. K. *J. Am. Chem. Soc.* **1987**, *109*, 1170.

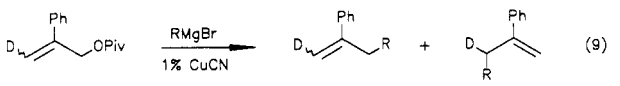
(9) There is a small isotope effect favoring the isomer in which the deuterium is on an sp^3 carbon; see ref 5b and Goering, H. L.; Paisley, S. D. *J. Org. Chem.* **1987**, *52*, 943.

These results are presented in eq 8 and contrast dramatically with the complete regiospecificity (exclusive γ-alkylation) observed for cross-coupling with alkyl Grignard reagents in the presence of catalytic CuCN.[5b]



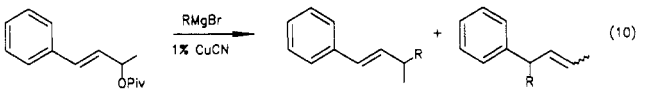
α-D-10-OMes	α-coupling	γ-coupling
R = Ph	54%	46%
R = propen-2-yl	54%	46%
R = n-Bu	0%	100%
R = i-Pr	0%	100%
R = t-Bu	0%	100%

Similarly, complete regiospecificity (γ-alkylation) is observed in cross coupling γ-deuterio-β-phenylallyl pivalate (γ-D-11-OPiv) with alkyl Grignard reagents in the presence of 1% CuCN, but regiospecificity is completely lost with PhMgBr/1% CuCN (eq 9).[5b]



γ-D-11-OPiv	α-coupling	γ-coupling
R = Ph	47%	53%
R = n-Bu	0%	100%
R = i-Pr	0%	100%
R = t-Bu	0%	100%

Another example in which phenylcuprates behave differently than alkylcuprates is shown in eq 10. Alkylation of *trans*-α-methyl-γ-phenylallyl pivalate (*trans*-**6**-OPiv) with *n*-BuMgBr in the presence of 1% CuCN gives 98% γ-alkylation and 2% α-alkylation, but phenylation with PhMgBr/1% CuCN gives 100% α-coupling (eq 10).[5b] Other workers have noted a similar lack of regiospecificity for reactions of allylic systems with phenyl- or vinylcuprates as compared to alkylcuprates.[10]



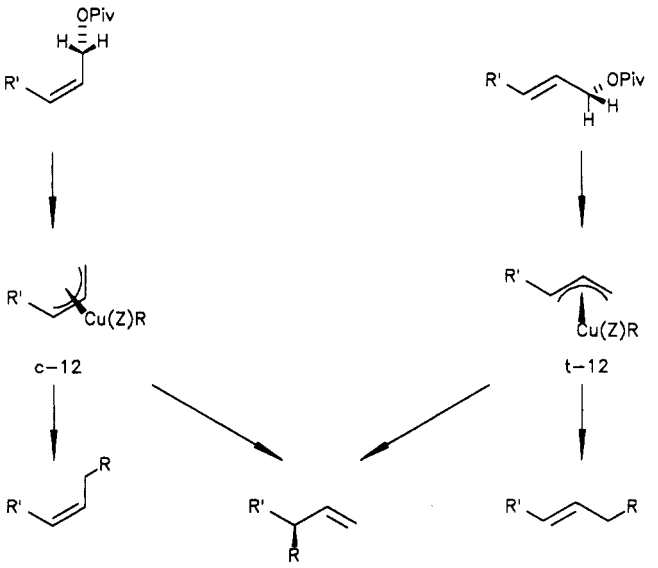
trans-6-OPiv	α-coupling	γ-coupling
R = n-Bu	2%	98%
R = Ph	100%	0%

Clearly the mechanism for cross-coupling allylic carboxylates with vinyl or phenyl (sp^2) organocopper reagents differs from that for alkyl (sp^3) organocopper reagents. In an earlier report[1] we proposed that the initial intermediate in cross coupling allylic carboxylates with phenylcuprates is a π-allylcopper(III) complex (**12**) rather than a (γ-σ-allyl)copper(III) complex (such as **1**, R = Ph, Scheme I) as with alkylcuprates. As shown in Scheme III, initial formation of a π-allylcopper(III) intermediate (**12**) accounts for the loss of regiospecificity in unbiased systems (such as cyclohexenyl, **10**-OMes, eq 8, and β-phenylallyl, **11**-OPiv, eq 9) and also accounts for α-phenylation in the α-methyl-γ-phenylallyl system (**6**-OPiv, eq 10). In the latter case, reductive elimination at the α-position gives the more stable conjugated product, which accounts for the observed regioselectivity.

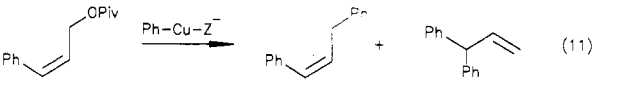
A corollary of the mechanism outlined in Scheme III is that the configuration of the double bond in the allylic ester should be preserved in the α-coupling product.

Results for cross coupling stereochemically pure[11] *cis*-cinnamyl pivalate (*cis*-**2**-OPiv) with a variety of phenyl-

Scheme III. Mechanism for Cross Coupling Allylic Carboxylates with Aryl- and Vinylcuprates

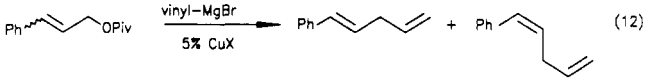


copper reagents are reported in eq 11. The product composition was determined by capillary GC and is independent of the phenylcopper reagent; in every instance the reaction regioselectively affords the α-substitution product with no detectable loss of double-bond configuration.



cis-2-OPiv		
$LiCuPh_2$	98%	2%
LiCu(CN)Ph	98%	2%
Ph_2CuMgI	98%	2%
PhMgBr/1% CuCN	98%	2%
PhMgBr/1% CuCl	98%	2%

Similar results were obtained for cross-coupling reactions of the cinnamyl system with vinylmagnesium bromide in the presence of 5% CuCN or CuCl. Reaction of *trans*-cinnamyl pivalate (*trans*-**2**-OPiv) with vinylmagnesium bromide/5% CuCN or 5% CuCl gives only one product as determined by capillary GC; this compound was determined by H NMR to be the conjugated product (eq 12). Cross coupling of pure *cis*-cinnamyl pivalate[11] with vinylmagnesium bromide/5% CuCN or 5% CuCl in ether at 0 °C also gives only the conjugated product with complete retention of double-bond configuration (eq 12).



trans-2-OPiv	X = Cl or CN	100%	0%
cis-2-OPiv	X = Cl or CN	0%	100%

Results for cross-coupling (*Z*,*E*)-**5**-OPiv with phenylcopper reagents are presented in eq 13. In all cases, the reaction regioselectively favored formation of the conjugated product (*Z*,*E*)-**13** (formed by α- and/or ε-coupling) and in no instance was any all-trans conjugated isomer ((*E*,*E*)-**13**) or cis,trans conjugated isomer ((*E*,*Z*)-**13**) detected in the product mixtures.[12] In certain cases, a small

E,E-13 E,Z-13

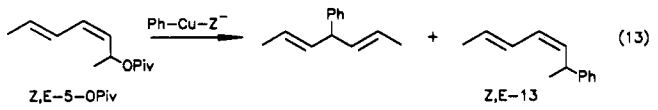
amount (<4%) of an unknown product was indicated by

(10) Marino, J. P.; Fernandez de la Pradilla, R.; Laborde, E. *J. Org. Chem.* **1987**, *52*, 4898.

(11) *cis*-**2**-OPiv can be cleanly separated from *trans*-**2**-OPiv by rotary TLC (silica gel, pentane–ether).

(12) Reich, H. J.; Wollowitz, S. *J. Am. Chem. Soc.* **1982**, *104*, 7051.

capillary GC. Preparative GC was unable to provide a homogeneous sample of the unknown; however, this product was shown by capillary GC to be neither (*E*,*E*)- nor (*E*,*Z*)-**13**.[12]

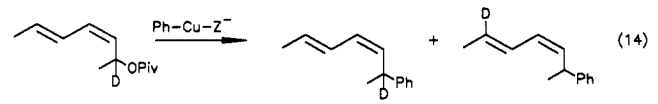


(13)

$LiCuPh_2$	8.3%	88.0%
LiCu(CN)Ph	8.2%	91.8%
PhMgBr/5% CuI[a]	16.9%	79.5%
PhMgBr/1% CuCN	35.5%	64.5%

[a] Unknown product present (<4%).

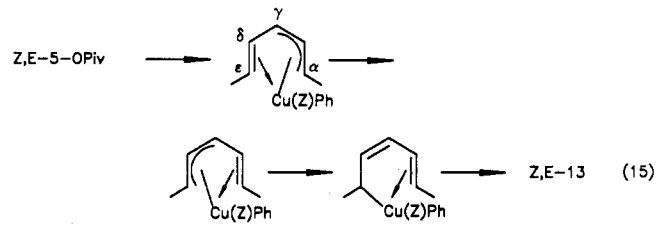
The ratio of α-coupling to ϵ-coupling in these phenylations was determined in a manner similar to that described for butylation of (*Z*,*E*)-**5**-OPiv. After reacting α-D-(*Z*,*E*)-**5**-OPiv with the phenylcopper reagents, the conjugated isomer was isolated by preparative GC, and the deuterium distribution was measured by integrating the appropriate signals in the ^1H NMR spectrum. The results are presented in eq 14 and show that α-coupling is the predominant pathway; hence, there is no loss of double-bond configuration in the α-coupling product.



(14)

α-D-Z,E-5-OPiv	α-coupling	ε-coupling
$LiCuPh_2$	67.1%	32.9%
LiCu(CN)Ph	67.1%	32.9%
PhMgBr/1% CuCN	77.2%	22.8%

It is noteworthy that only one stereoisomer, (*Z*,*E*)-**13**, is produced as a result of ϵ-coupling. Evidently the ϵ-phenylation product arises from an internally chelated σ-allylcopper(III) intermediate, which enforces a cis geometry about the newly formed C_γ–C_δ double bond (eq 15). Keinan et al.[13] has proposed a similar (γ-σ-allyl)copper(III) chelate intermediate to account for formation of cis olefin in the cross coupling of cyanocuprates with an enynyl system.



(15)

The complete preservation of original double-bond configuration and absence of regiospecificity with aryl and vinyl (sp^2) cuprates supports the view that with these reagents oxidative addition results in the direct formation of a π-allylcopper(III) complex (**12**) as shown in Scheme III. This is in sharp contrast to the mechanistic pathway for alkyl (sp^3) cuprates in which case oxidative additive clearly involves a (γ-σ-allyl)copper(III) complex (**1**) as shown in Scheme I. The reason for the difference in the mechanistic pathways for sp^2 and sp^3 reagents is not known.

Experimental Section

General Methods. All reactions were carried out under a positive pressure of dry nitrogen. Grignard reagents and cuprous salts were prepared and purified as described earlier.[5b] *n*-BuLi (2.5 M in hexanes), PhLi (2.0 M in 7:3 cyclohexane–ether) and vinylmagnesium bromide (1.0 M in THF) were purchased from Aldrich Chemical Co.

Mass spectra were recorded with an AEI-MS-902 high-resolution mass spectrometer. Proton NMR spectra were obtained with a Bruker WP200 instrument; ^{13}C NMR spectra were obtained with a JEOLCO FX-200 spectrometer operated at 50.1 MHz, and chemical shifts are referenced to the center peak of the $CDCl_3$ triplet (77.0 ppm). Coupling constants are in hertz. Infrared spectra were obtained with a Polaris FT IR spectrometer and are reported in reciprocal centimeters.

Materials. *cis*-Crotyl pivalate (*cis*-4-OPiv) was prepared in the usual manner[1] from *cis*-crotyl alcohol[14] and pivaloyl chloride and had the following properties: bp 59–60 °C (27 mm); NMR (δ, $CDCl_3$) 5.44–5.79 (m, 2 H), 4.61 (dd, 2 H, J = 7.0, 1.1), 1.69 (dd, 3 H, J = 8.0, 1.0), 1.18 (s, 9 H); high-resolution mass spectrum calcd for $C_9H_{16}O_2$ m/e 156.1150, found m/e 156.1155.

***trans*-Crotyl pivalate (*trans*-4-OPiv)** was prepared as above from *trans*-crotyl alcohol[15] and pivaloyl chloride and had the following characteristics: bp 60–61 °C (15 mm); IR (neat) 3020–2850 (s), 1730 (s), 1485 (s), 1460 (m), 1400 (m), 1370 (m), 1285 (s), 1160 (s), 1040 (m), 970 (s), 775 (m); NMR (δ, $CDCl_3$) 5.76 (dqt, 1 H, J = 16.0, 6.1, 1.0), 5.58 (dtq, 1 H, J = 16.0, 6.1, 1.3), 4.49 (dd, 2 H, J = 6.1, 1.0), 1.72 (dd, 3 H, J = 6.1, 1.3), 1.20 (s, 9 H); high-resolution mass spectrum calcd for $C_9H_{16}O_2$ m/e 156.1150, found m/e 156.1148.

(*Z*,*E*)-3,5-Heptadien-2-ol ((*Z*,*E*)-5-OH) was prepared as reported earlier:[16] NMR (δ, $CDCl_3$) 6.36 (br dd, 1 H, J = 16.2, 10.6), 5.96 (app t, 1 H, J = 10.8), 5.76 (dq, 1 H, J = 16.1, 7.0), 5.31 (app t, 1 H, J = 10.6), 5.80 (app p, 1 H, J = 6.8), 1.78 (d, 3 H, J = 7.0), 1.48 (br s, 1 H), 1.28 (d, 3 H, J = 6.8).

(*Z*,*E*)-3,5-Heptadien-2-yl pivalate ((*Z*,*E*)-5-OPiv) was prepared as usual[1] from (*Z*,*E*)-**5**-OH[16] and pivaloyl chloride and was purified by rotary TLC (ether–pentane, silica gel) and had the following properties: NMR (δ, $CDCl_3$) 6.40 (br dd, 1 H, J = 16.2, 10.6), 5.99 (app t, 1 H, J = 10.6), 5.8–5.8 (m, 2 H, computer simulation[17] indicates multiplet consists of a signal at δ 5.74, app p, J = 6.6, and a signal at δ 5.76, dq, J = 16.2, 6.4), 5.23 (app t, 1 H, J = 10.6), 1.79 (d, 3 H, J = 6.4), 1.29 (d, 3 H, J = 6.6), 1.18 (s, 9 H); ^{13}C NMR ($CDCl_3$) 177.8, 132.1, 130.6, 127.8, 126.5, 66.9, 38.6, 27.1, 20.8, 18.3; high-resolution mass spectrum calcd for $C_{12}H_{20}O_2$ m/e 196.1464 found m/e 196.1464.

α-Deuterio-(*Z*,*E*)-3,5-heptadien-2-yl pivalate (α-D-(*Z*,*E*)-5-OPiv) was prepared as described above for the preparation of unlabelled (*Z*,*E*)-**5**-OPiv. The corresponding alcohol was obtained by $LiAlD_4$ reduction of (*Z*,*E*)-3,5-heptadienone.[16]

General Procedure for Copper(I)-Catalyzed Cross-Coupling of Pivalates 2, 4, and 5 with Grignard Reagents. The pivalates (1 mmol) were dissolved in 6 mL of dry ether, and an appropriate amount of cuprous salt (1–5% with respect to Grignard reagent) was added. The resulting mixture was cooled to the indicated temperature, and a 2 M excess of an ethereal solution of Grignard reagent (or a THF solution of vinylmagnesium bromide) was added. After standard workup,[5b] products were isolated by rotary TLC.

General Procedure for Cross-Coupling Pivalates 2, 4, and 5 with $LiCuR_2$ and LiCu(CN)R is the same as reported earlier.[1]

(*E*)-1-Phenyl-1,4-pentadiene: NMR (δ, $CDCl_3$) 7.2–7.4 (m, 5 H), 6.41 (d, 1 H, J = 15.9), 6.21 (dt, 1 H, J = 15.9, 6.4), 5.91 (ddt, 1 H, J = 17.1, 10.1, 6.4), 5.12 (ddt, 1 H, J = 17.1, 1.8, 1.3), 5.06 (br d, 1 H, J = 10.1), 2.95 (app tq, 2 H, J = 6.4, 1.3).

(*Z*)-1-Phenyl-1,4-pentadiene: NMR (δ, $CDCl_3$) 7.2–7.4 (m, 5 H), 6.53 (d, 1 H, J = 11.9), 5.90 (ddt, 1 H, J = 17.1, 10.6, 5.9), 5.71 (dt, 1 H, J = 11.9, 7.6), 5.12 (d, 1 H, J = 17.1), 5.06 (d, 1 H, J = 10.6), 3.04 (app ddq, 2 H, J = 7.6, 5.9, 1.6).

(*E*)-4-((*E*)-1-Propenyl)-2-octene ((*E*,*E*)-7): IR (neat) 3010 (m), 2970 (s), 2940 (s), 2880 (s), 1450 (m), 1360 (w), 950 (s); NMR (δ, $CDCl_3$) 5.2–5.5 (m, 4 H), 2.54 (app p, 1 H, J = 6.6), 1.66 (d, 6 H, J = 5.5), 1.2–1.4 (m, 6 H), 0.88 (br t, 3 H, J = 6.4); ^{13}C NMR

(13) Keinan, E.; Bosch, E. *J. Org. Chem.* **1986**, *51*, 4006.

(14) Knights, J.; Waight, E. S. *J. Chem. Soc.* **1955**, 2830.

(15) Hatch, L. F.; Nesbit, S. S. *J. Am. Chem. Soc.* **1950**, *72*, 727.

(16) Kluge, A. F.; Lillya, C. P. *J. Org. Chem.* **1971**, *36*, 1988. Porter, N. A.; Roberts, D. H.; Ziegler, C. B., Jr. *J. Am. Chem. Soc.* **1980**, *102*, 5912.

(17) Computer simulation of ^1H NMR spectra was done with the RACCOON program by Paul F. Schatz.

(δ, $CDCl_3$) 135.1, 123.8, 45.8, 35.2, 29.6, 22.8, 17.9, 14.1; high-resolution mass spectrum calcd for $C_{11}H_{20}$ m/e 152.1566, found m/e 152.1566.

(E)-4-((Z)-1-Propenyl)-2-octene ((E,Z)-7) obtained by preparative GC was contaminated with ≈50% (E,E)-7 and had the following properties: IR (neat) 3010 (m), 2970 (s), 2940 (s), 2880 (s), 1450 (m), 1360 (w), 950 (s); NMR (δ, $CDCl_3$) 5.1-5.6 (m, 4 H), 2.97 (app p, 0.47 H, J = 6.5), 2.54 (app p, 0.53 H, J = 6.6), 1.6-1.7 (three overlapping doublets, 6 H), 1.2-1.4 (m, 6 H), 0.88 (br t, 3 H, J = 6.4); ^{13}C NMR (corrected for (E,E)-7, δ, $CDCl_3$) 134.7, 134.2, 123.4, 122.9, 44.2, 40.2, 25.5, 24.3, 23.3, 22.3, 13.0; determination of the stereoisomer ratio was accomplished by integration of the methine resonances in the ^1H NMR: δ 2.54 ((E,E)-7) and δ 2.97 ((E,Z)-7).

(E,Z)-6-Methyl-2,4-decadiene ((E,Z)-8): IR (neat) 3010 (m), 3000 (w), 2960 (s), 2930 (s), 2880 (s), 2860 (s), 1420 (m), 1390 (m), 990 (s), 960 (s), 830 (m); NMR spectrum including decoupling experiments led to the assignment of (E,Z)-8 (δ, $CDCl_3$) 6.31 (dd, 1 H, J = 14.9, 10.9), 5.89 (app t, 1 H, J = 10.9), 5.65 (dq, 1 H, J = 14.9, 6.8), 5.06 (app t, 1 H, J = 10.9), 2.55 (m, 1 H), 1.78 (d, 3 H, J = 6.8), 1.22 (m, 6 H), 0.95 (d, 3 H, J = 6.6), 0.84 (t, 3 H, J = 6.8); high-resolution mass spectrum calcd for $C_{11}H_{20}$ m/e 152.1566, found m/e 152.1566.

(E,E)-6-Methyl-2,4-decadiene ((E,E)-8): IR (neat) 3010 (m), 2950 (s), 2920 (s), 2860 (s), 1470 (m), 1460 (m), 1380 (m), 990 (s); NMR including decoupling experiments led to the assignment of (E,E)-8 (δ, $CDCl_3$) 6.04 (ddd, 1 H, J = 14.1, 10.3, 1.5), 5.96 (dd, 1 H, J = 14.3, 10.3), 5.56 (dq, 1 H, J = 14.1, 6.5), 5.43 (dd, 1 H, J = 14.3, 7.8), 2.10 (m, 1 H), 1.73, (dd, 3 H, J = 6.8, 1.5), 1.27 (m, 6 H), 0.98 (d, 3 H, J = 6.6), 0.87 (t, 3 H, J = 6.8); high-resolution mass spectrum calcd for $C_{11}H_{20}$ m/e 152.1566, found m/e 152.1566.

(E,E)-4-Phenyl-2,5-heptadiene: IR (neat) 3090 (w), 3070 (w), 3020 (s), 2970 (s), 2940 (s), 2920 (s), 2880 (w), 2860 (m), 1500 (m), 1450 (s), 980 (s), 760 (m), 700 (s); NMR (δ, $CDCl_3$) 7.2-7.4 (m, 5 H), 5.64 (ddq, 2 H, J = 15.2, 6.8, 1.3), 5.47 (dqd, 2 H, J = 15.2, 5.9, 0.6), 3.94 (br t, 1 H, J = 6.8), 1.70 (ddd, 6 H, J = 5.9, 1.3, 0.9); high-resolution mass spectrum calcd for $C_{13}H_{16}$ m/e 172.1253, found m/e 172.1254.

(E,Z)-6-Phenyl-2,4-heptadiene ((E,Z)-13): IR (CCl_4) 3070 (w), 3020 (s), 2980 (s), 2940 (s), 2935 (s), 2870 (m), 1500 (s), 1450 (s), 980 (m), 950 (m), 600 (s); NMR (δ, $CDCl_3$) 7.1-7.5 (m, 5 H), 6.44 (dd, 1 H, J = 15.0, 10.4), 5.96 (app t, 1 H, J = 10.4), 5.72 (dq, 1 H, J = 15.0, 6.6), 5.40 (app t, 1 H, J = 10.4), 3.92 (br dq, J = 10.4, 6.9), 1.79 (d, 3 H, J = 6.6), 1.38 (d, 3 H, J = 6.9); high-resolution mass spectrum calcd for $C_{13}H_{16}$ m/e 172.1253, found m/e 172.1254.

Determination of Deuterium Distribution in the Coupling Products Derived from α-D-(Z,E)-5-OPiv. Reaction of α-D-(Z,E)-5-OPiv with organocopper reagents was carried out according to the general procedures, and conjugated products (8 or 13) were separated from unconjugated products by preparative GC. Integration of the methine resonances in the ^1H NMR ((E,E)-8, δ 2.10; (E,Z)-8, δ 2.55; (E,Z)-13, δ 3.92) proved a convenient and reproducible method for determining the deuterium distribution. Duplicate runs gave identical (±2%) results, and control experiments indicated that 2% was the lower limit of detection.

Acknowledgment. This work was supported by the National Science Foundation (Grant CHE-8406480).

Registry No. *cis*-2-OPiv, 119819-17-9; *trans*-2-OPiv, 80006-87-7; *cis*-4-OPiv, 119819-13-5; *trans*-4-OPiv, 119819-14-6; (Z,E)-5-OPiv, 119819-15-7; α-(Z,E)-5-OH, 84838-74-4; α-D-(Z,E)-5-OPiv, 119819-16-8; (E,E)-7, 119819-18-0; (E,Z)-7, 119819-19-1; (E,E)-8, 119819-21-5; (E,E)-8 (α,ε-D), 119819-23-7; (E,Z)-8, 119819-20-4; (E,Z)-8 (α,ε-D), 119850-51-0; (E,Z)-13, 68099-40-1; CuCN, 544-92-3; CuCl, 7758-89-6; BuMgBr, 693-03-8; $LiCuBu_2$, 24406-16-4; BuMgI, 1889-20-9; LiCu(CN)Bu, 41742-63-6; $LiCuPh_2$, 23402-69-9; LiCu(CN)Ph, 41742-64-7; Ph_2CuMgI, 51340-38-6; PhMgBr, 100-58-3; $H_2C{=}CHMgBr$, 1826-67-1; (Z,E)-$H_3CCH(OH)CH{=}CHCH{=}CHCH_3$, 84838-74-4; (E)-$C_6H_5CH{=}CHCH_2Bu$, 10201-58-8; $C_6H_5CH(Bu)CH{=}CH_2$, 40395-23-1; (Z)-$C_6H_5CH{=}CHCH_2Bu$, 10201-59-9; (Z)-$BuCH_2CH{=}CHCH_3$, 7642-04-8; $H_2C{=}CHCH(Bu)CH_3$, 4810-09-7; (E)-$BuCH_2CH{=}CHCH_3$, 13389-42-9; $H_2C{=}CHCH(Bu)CH_3$, 4810-09-7; (Z)-$C_6H_5CH{=}CHCH_2C_6H_5$, 1138-83-6; $(C_6H_5)_2CHCH{=}CH_2$, 3542-14-1; (E,E)-$H_3CCH{=}CHCH(C_6H_5)CH{=}CHCH_3$, 119819-22-6; (E,Z)-$H_3CCH{=}CHCH{=}CHCD(C_6H_5)CH_3$, 119850-52-1; (E,Z)-$H_3CCD{=}CHCH{=}CHCH(C_6H_5)CH_3$, 119819-24-8; (E)-1-phenyl-1,4-pentadiene, 55666-17-6; (Z)-1-phenyl-1,4-pentadiene, 97632-25-2; *trans*-crotyl alcohol, 504-61-0; (Z,E)-3,5-heptadienone, 4857-17-4; *cis*-crotyl alcohol, 4088-60-2; pivaloyl chloride, 3282-30-2; lithium dimethylcuprate, 15681-48-8.

Asymmetric Alkylation of β-Keto Esters with Optically Active Sulfonium Salts

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Alkylation of the cyclic β-keto ester 2-(methoxycarbonyl)-1-indanone (**2**) with racemic alkylsulfonium salts **1a-h** gave 2-alkylindanones **3** and **4** in 60-96% yields. The relative reactivities of the alkyl substituents of aryldialkylsulfonium salts **1e** and **1f** were quite different from those in S_N2 alkylations. Asymmetric induction occurred upon alkylation of **2** with optically active sulfonium salts. (*R*)-2-Ethyl-2-(methoxycarbonyl)cyclohexanone (**11**) was obtained in up to 16% ee by alkylation of the enolate ion of 2-(methoxycarbonyl)cyclohexanone (**9**) with optically active (*R*)-(+)-(*p*-chlorophenyl)ethylmethylsulfonium *d*-10-camphorsulfonate (**1k**). Alkylation of the enolate ion of **2** with sulfonium salts containing optically active alkyl groups afforded C-alkylated products with inversion of configuration at the asymmetric alkyl carbon atom. These alkylations appear to proceed via an S-O sulfurane intermediate or a tight ion pair with subsequent stereoselective alkyl migration to the enolate.

Introduction

Recently, extensive studies have been published on asymmetric syntheses with enantiomerically pure sulfoxides.[1] However, little has been reported on the use of optically active sulfonium salts in asymmetric syntheses, except for the use of optically active sulfonium ylides prepared by deprotonation of sulfonium salts with strong bases.[2] Moreover, few chiral sulfonium salts have been

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(2) (a) Asymmetric epoxidation: Johnson, C. R.; Schroeck, C. W. *J. Am. Chem. Soc.* **1973**, *95*, 7418 and 7424. (b) Trost, B. M.; Hammen, R. F. *J. Am. Chem. Soc.* **1973**, *95*, 962.

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