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IODINE ATOM TRANSFER ADDITION REACTIONS WITH ALKYNES. PART 1: ALKYL IODIDES

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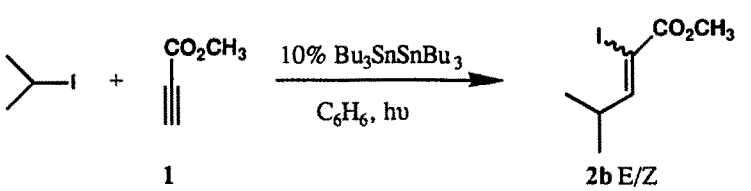
Summary: Simple 2°- and 3°-alkyl iodides add smoothly to electron deficient alkynes under standard atom transfer conditions (10% $Bu_3SnSnBu_3$, sunlamp photolysis). Mechanistic experiments help to interpret stereochemical and yield trends, and a new model for atom abstraction reactions of rapidly inverting σ-vinyl radicals is proposed.

Introduction: Radical addition reactions have emerged as useful preparative methods[2] thanks to a detailed understanding of substituent effects on rates of additions of radicals to multiple bonds.[3] Appropriate electronic pairing is important, and most radical additions pair nucleophilic (alkyl) radicals with electron deficient alkenes or alkynes. Reductive additions based on tin[4] and silicon[5] hydrides and non-reductive additions based on allyl stannanes,[6] thiohydroxamate acid esters,[7] or alkyl cobalts[8] are especially general, but other methods are also available.[2d] Additions of electrophilic radicals to nucleophilic alkenes are also favorable,[9] and the atom transfer method is especially useful for such reactions.[10] There are very few examples of atom transfer *addition* reactions with alkyne acceptors,[11] but we found that alkynes were excellent acceptors in iodine atom transfer *cyclization* reactions.[12] We report here the complete details of a study which begins to delineate the scope and limitations of iodine atom transfer addition reactions of alkyl iodides to alkynes.[13] Sunlamp photolysis of iodides and alkynes in the presence of 10% hexabutylditin produces vinyl iodide adducts in yields that vary widely as a function of the structure of both the radical precursor and the alkyne. A few of these results have already been cited in a review and a conference preceding,[14] and after our work was complete, Utimoto and Oshima also showed that triethylboron is a useful additive that can replace ditin in such reactions.[15]

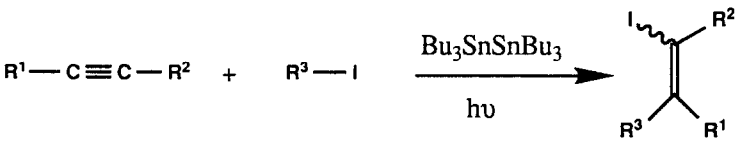
Preparative Studies: Nucleophilic alkyl radicals add well to electron deficient alkenes, and it is generally thought that alkynes are only marginally less reactive than related alkenes.[16] Guided by this, we initially studied the atom transfer addition of isopropyl iodide to methyl propiolate (**1**) (eq 1) under the standard conditions that we had developed for related cyclizations.[12] Sunlamp irradiation (1 h) of an 0.3 M benzene solution of isopropyl iodide (1 equiv), **1** (1 equiv), and hexabutylditin (0.1 equiv) formed **2b** (E/Z mixture) in 46% isolated yield. About the same yield was obtained when excess methyl propiolate (2.5 equiv) was used, but the yield increased to 70% (isolated) when excess isopropyl iodide (2.5 equiv) was used. Isomers **2bE** and **2bZ** formed in a ratio of 22/78, and we were able to separate them by flash chromatography. We assigned stereochemistry based on the chemical shifts of the vinyl protons.[17]



1 **2b** E/Z eq 1

Table 1 presents the results of this series of experiments designed to explore the generality of this procedure. We selected *n*-butyl iodide, isopropyl iodide, *tert*-butyl iodide as representative iodides (one experiment was also conducted with benzyl iodide), and methyl (and ethyl) propiolate, phenyl acetylene, dimethyl acetylenedicarboxylate, and phenylsulfonyl acetylene[18] as activated acceptors. To probe for electronic effects, we also included the unactivated alkyne 1-heptyne, which is 20 times less reactive than phenyl acetylene towards methyl radicals.[19] Reaction mixtures were irradiated for 30 or 60 min, and 2.5 equiv of iodide was used in every case. The temperature of the reaction was not controlled, and we estimate that the heat from the sunlamp quickly warmed the mixture to 80-85°C. In two cases, reactions did not occur at this temperature, and the reaction mixtures were sealed and irradiated at ~180°C. Vinyl iodides formed in all cases save one, and Table 1 records the isolated yields of these iodides after purification by flash chromatography. More often than not, the E/Z isomers were not easily

Table 1. Iodine Atom Transfer Additions of Alkyl Iodides to Alkynes.



	Alkyne	Alkyl Iodide	Vinyl Iodide	E/Z	Conditions[a]	Yield[b]
1	R_1 = H, R_2 = CO_2Me	R_3 = *n*-Bu	**2a**	1/2.4	A	14%
		R_3 = *i*-Pr	**2b**	1/2.4	A	70%
		R_3 = *t*-Bu	**2c**	4/1	A	70%
3	R_1 = H, R_2 = CO_2Et	R_3 = *i*-Pr	**4b**	1/2.9	A	79%
		R_3 = *t*-Bu	**4c**	2.4/1	A	80%
5	R_1 = H, R_2 = Ph	R_3 = *n*-Bu	**6a**	1/1.5	B	19%
		R_3 = *i*-Pr	**6b**	1/2.9	B	56%
		R_3 = *t*-Bu	**6c**	2.8/1	B	60%
		R_3 = Bn	**6d**	1.4/1	B	35%
7	R_1 = R_2 = CO_2Me	R_3 = *n*-Bu	**8a**	–	A	d
		R_3 = *i*-Pr	**8b**	4.6/1	A	81%
		R_3 = *t*-Bu	**8c**	1/3.2	A	60%
9	R_1 = H, R_2 = SO_2Ph	R_3 = *n*-Bu	**10a**	1/14	A	18%
		R_3 = *i*-Pr	**10b**	1/17	A	61%
		R_3 = *t*-Bu	**10c**	1/190	A	83%
11	R_1 = H, R_2 = *n*-Bu	R_3 = *n*-Pr	**12a**	1/3	C	13%
		R_3 = *i*-Pr	**12b**	1/2.4	B	39 (64%)[c]
		R_3 = *t*-Bu	**12c**	3.1/1	B	22%

[a]All the addition reactions were performed in benzene with the alkyne (1 equiv), alkyl iodide (2.5 equiv) and hexabutylditin (10 mol% relative to alkyl iodide) with 275w GE sunlamp initiation. Reaction time and temperature: A, 30 min at 80-85°C; B, 1 h at 80-85°C; C, in a sealed tube, 30 min at ~180°C. [c]Yield determined by ^{1}HMR. [d]Polymerization was observed.

separated. Stereochemistries were generally assigned based on known deshielding trends for either the allyl or vinyl protons.[17] Adduct **8c** has neither allyl nor vinyl protons, and its stereochemistry was assigned only by analogy; this assignment should be regarded as tentative.

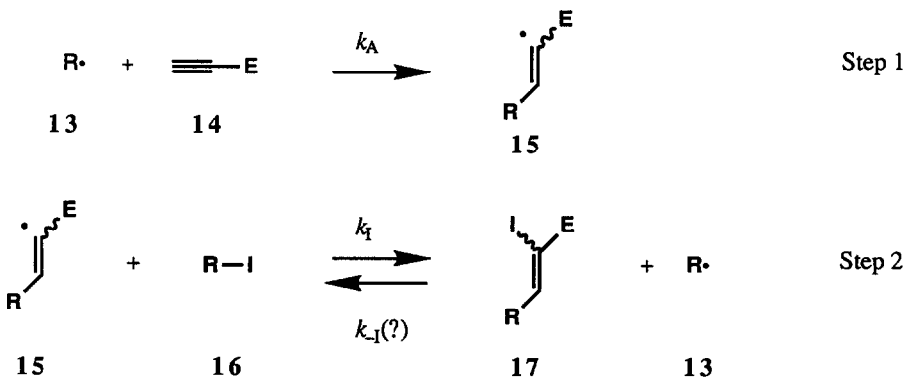
Both yield and stereochemical trends emerged from this series of experiments. First, adducts formed in good yields (56-83%) in all of the reactions between isopropyl iodide or *tert*-butyl iodide and each of the activated alkynes. Poor yields from these iodides were obtained only with the unactivated alkyne, 1-hexyne. In contrast, *n*-butyl iodide gave poor yields (<20%) with all of the acceptors. Benzyl iodide also gave a rather poor yield in the one preparative experiment that we tried (**6d**), and it was not used further. Second, with ester-, phenyl-, and alkyl-substituted alkynes, we always isolated a slight excess of the isomer with the alkyl group and the iodide cis with the *n*-butyl and isopropyl iodide (these are usually Z isomers, but a change in CIP priority rules makes them E isomers for **8b**), whereas with *tert*-butyl iodide these groups were trans. The E/Z ratios varied slightly from one experiment to the next, and mechanistic studies (see below) showed that this was due to partial equilibration of the iodides. In contrast, phenylsulfonyl acetylene gave good to excellent Z-selectivity (**10a-c**) with all three iodides.

Under these standard conditions, the addition of 1°-iodides to activated alkynes is not a preparatively useful process; however, the addition of 2°- or 3°-iodides does have potential utility as an alternative to standard organometallic conjugate addition processes. The additions to phenylsulfonyl acetylenes are especially attractive because they are both high-yielding and highly Z-selective.

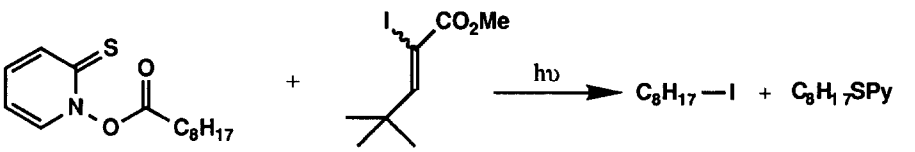
Mechanistic Studies: Scheme 1 outlines mechanistic considerations for the atom transfer addition of alkyl iodides to alkynes. An alkyl radical **13** (generated either in an initiation step or an atom transfer step) undergoes irreversible addition to the alkyne **14** (step 1) to give vinyl radical **15**. Because there are no added trapping reagents (like tin hydride), the alkyl radical **13** will have a relatively long lifetime in which to undergo the addition. The intermediate vinyl radical **15** then abstracts an iodine atom from the alkyl iodide **16** to give the product vinyl iodide **17** and the starting alkyl radical **13**. In our studies on atom transfer cyclizations of alkyl iodides to *unactivated* alkynes,[12] we learned that the atom transfer step was for all practical purposes irreversible. However, in these bimolecular reactions, the activating group (**E**) that accelerates the radical addition (step 1) might also stabilize the intermediate radical **15**. This is undesirable for two reasons. First, radical stabilizing groups could reduce the rate of iodine atom transfer (due to reduced exothermicity of the reaction), and this would compromise the viability of the chain. Second, even if the iodine transfer reaction were still fast due to polar effects, its reduced exothermicity (or even endothermicity?) could permit the reverse iodine transfer to occur. This places products **17** at risk by returning them to radicals. The intermediacy of vinyl radicals is important in these chains. If activated alkenes (for example, methyl acrylate) are used, the adduct radicals are significantly more stable than the starting radicals, and iodine transfer chains will not propagate. Stated another way, chains will not propagate if the product iodides are much better iodine donors than the starting iodides.

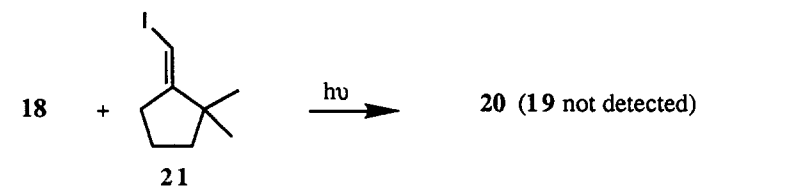
Why do 1°-iodides give much poorer yields than 2°- or 3°-iodides? Low rates in the addition (step 1) will lead to difficulties in chain propagation. This may be why very high temperatures are needed to attain modest yields with the unactivated alkynes. 1°-Alkyl radicals are less nucleophilic than their 2°- and 3°-counterparts, so low addition rates may contribute to the poor yields with *n*-butyl iodide and activated alkynes. Low exothermicity (or even endothermicity) in the iodine transfer step might also be the reason why *n*-butyl iodide is a much poorer substrate than the 2°- and 3°-iodides. We addressed the question of

Scheme 1



whether a 1°-radical could abstract iodine from a typical adduct (reverse of step 2) by using Newcomb's kinetic adaptation of the Barton method (eq 2).[20] Both the procedure and analysis have been described elsewhere.[21] When thiohydroxamate ester **18** (1 equiv) was photolyzed in benzene (50°C, 1 min, 0.05M) in the presence of vinyl iodide **2c** (4.7 equiv, E/Z mixture), octyl iodide (**19**) and octyl thiopyridine (**20**) were produced in a ratio of 1.9/1 (eq 2). From the known rate constant for formation of octylthiopyridine,[20] we can estimate the rate constant for iodine transfer: $k_I \approx 5 \times 10^5$ M^{-1} s^{-1}. This rate constant should be regarded as very approximate, especially since we did not consider the possibility that iodine transfer is reversible (however, we did use excess iodide **2c** to minimize this reaction). We conducted a similar experiment with thiohydroxamate **18** and vinyl iodide **21** (eq 3). Here the iodine transfer is significantly endothermic, and no octyl iodide **19** was detected.





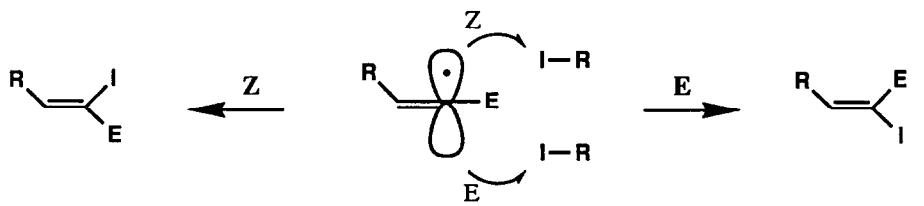
Rate constants for the reactions of 1°-radicals with representative iodides are collected in Table 2.[20,21] Vinyl iodide **2c** is about as good an iodine donor toward a 1°-radical as a 1°- or 2°-iodide. We cannot say anything about the relative stability of the vinyl radical derived from **2c** because we do not know the back rate constant. However, that the product is a reasonably potent iodine donor with respect to the starting radical is clearly a problem.

Table 2. Rate Constants for Iodine Atom Transfer from Various Alkyl Iodides toward Octyl Radical in Benzene at 50 ± 2°C.

iodine donor	k ($M^{-1}sec^{-1}$)
ICH_2CO_2Et	2×10^7
t-butyl iodide	$(3 \pm 2) \times 10^6$
i-propyl iodide	$(9.5 \pm 2.8) \times 10^5$
c-hexyl iodide	$(5.4 \pm 0.9) \times 10^5$
2c	$\sim 5 \times 10^5$
ethyl iodide	$(3.4 \pm 0.4) \times 10^5$

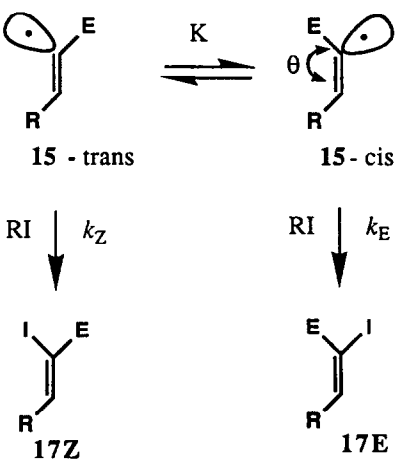
Scheme 2 analyzes stereochemical options in the atom transfer step in more detail. Vinyl radicals typically have very low inversion barriers,[22] so we discard the possibility that iodine transfer is faster than equilibration of an initially formed intermediate. Two kinetic possibilities remain (Scheme 2a,b): 1) the vinyl radical could be linear (**15**-linear), and stereochemistry would be dictated by the rates of iodine transfer from each side of the radical, or 2) the vinyl radical could be bent and rapidly inverting (**15** trans/cis), and the stereochemistry would be dictated by the relative populations of the two isomeric radicals (equilibrium constant) and their individual rates of iodine transfer (Curtin-Hammet kinetics).[23]

Scheme 2a. Linear Vinyl Radical



17Z 15-linear 17E

Scheme 2b. Rapidly Inverting Vinyl Radical



In surveying reaction conditions with isopropyl iodide and methyl propiolate, we observed that E/Z ratios of product **2b** varied somewhat from one experiment to the next. Further, the rate study with vinyl iodide **2c** (eq 2) indicated that return of the vinyl iodide to a radical was possible, and such a reversible iodine transfer provides a mechanism for E/Z isomerization. To learn more about the kinetic and thermodynamic control in the iodine transfer, we followed several reactions more carefully to determine E/Z ratios as a function of reaction time.

Atom transfer addition reactions of *n*-butyl iodide, isopropyl iodide and *tert*-butyl iodide to phenyl acetylene were monitored by ^{1}H NMR (C_6D_6), and the absolute yields of the product vinyl iodides as a function of time were measured by integration against an internal standard (1,4-dichlorobenzene). The data in Table 3 show that the E isomer predominates at very low conversion for all iodides, but that the E/Z ratio quickly decreases due to equilibration. There is no evidence that the ratios at the shortest times represent the true kinetic ratios, but we believe that the trend is secure: E-selectivity increases in the order 1°< 2°< 3°-iodide. At very low conversion, the addition of *tert*-butyl iodide appears to be completely E-selective. Styryl radicals are thought to be linear,[24] and our kinetic stereochemical trends are consistent with this structure. As the size of the R group in **15**-linear increases, the E-selectivity also increases (Scheme 2a). There is also no evidence that the final ratios are the true thermodynamic ratios. Irradiation of a purified sample of **6bE** for 1 h under the reaction conditions led to an E/Z ratio of 15/85. Prolonged irradiation led to significant decomposition of the products; however, it is probable that the Z-isomers are thermodynamically favored for all the adducts.

Table 3. Iodine Atom Transfer Addition of Alkyl Iodides to Phenylacetylene.[a]

	R = *n*-Bu	R = *i*-Pr	R = *t*-Bu
Time	E/Z (Yield of **6a**)	E/Z (Yield of **6b**)	E/Z (Yield of **6c**)
0.5 min	n.d.	83/17	n.d.
1 min	n.d.	63/38 (2%)	n.d.
2 min	53/47 (1%)	n.d.	>95/5 (4%)
5 min	n.d.	55/45 (6%)	n.d.
10 min	42/58 (3%)	55/45 (9%)	95/5 (20%)
30 min	42/58 (4%)	n.d.	83/17 (24%)
60 min	n.d.	n.d.	82/18 (19%)
120 min	34/66 (5%)	n.d.	69/31 (11%)

[a]A solution of the iodide (1 equiv), phenylacetylene (1 equiv), hexabutylditin (10%), and the internal standard (1,4-dichlorobenzene) in C_6D_6 (0.3 M) was irradiated with a sunlamp.

n.d. = not determined

The additions to propiolate derivatives were more difficult to study because the reactions were faster, and it was difficult to get ratios at early conversions. However, we were able to show that isomerization did occur to some extent in the addition of isopropyl iodide to methyl propiolate. Table 4 collects the results of this experiment. After 2 min of irradiation of a mixture of methyl propiolate and isopropyl iodide, there was a slight excess of the Z-isomer **2bZ** already present, and this increased by a small but significant amount over the next 30 min. Again, only the trend is clear, and we do not know either the kinetic or thermodynamic ratios.

Table 4. Iodine Atom Transfer Addition of *iso*-Propyl Iodide to Methyl Propiolate.

Time	Yield **2b** (%)	E/Z
2 min	10	45/55
1 min	27	32/68
30 min	42	27/73
60 min	42	26/74

The change in stereochemistry in the *tert*-butyl iodide addition was more difficult to study because the reaction was even faster, and we could not get a ratio at <20% conversion. However, a pair of careful control experiments shown in Table 5 provided evidence that the increased E-selectivity in the *tert*-butyl iodide additions was not the result of a dramatic change in relative thermodynamic stabilities of the E and Z isomers. Purified vinyl iodide **2c** (69/31, E/Z) was irradiated with a sunlamp in the presence and absence of ditin. In the absence of ditin, the rate of isomerization was somewhat slower, but the mass balance was excellent. After 1 h, a 50/50 ratio of E/Z isomers was present. As expected, significant decomposition occurred on prolonged irradiation with ditin (tributyltin iodide and other unidentified products were produced), but E/Z isomerization still occurred.[25]

Table 5. Isomerization of the Vinyl Iodide **2c**.

	with Bu_6Sn_2	without Bu_6Sn_2
Time(min)	E/Z (mass balance)	E/Z (mass balance)
0	69/31	69/31
10	58/42 (83%)	63/37 (93%)
30	42/58 (54%)	57/43 (87%)
60	33/67 (46%)	50/50 (90%)

Photolytic isomerizations of vinyl iodides have been known for some time, and various mechanisms have been proposed.[26] The mechanism for isomerization of the above iodides is not entirely clear, and we consider three possibilities. First, direct photoisomerization of the triplet state of the vinyl iodide is possible, but it seems very unlikely that sunlamp irradiation through Pyrex glass could provide sufficient energy. Second, molecular iodine is a well known catalyst for olefin isomerizations.[27] However, the isomerization proceeds more rapidly in the presence of ditin (an excellent iodine scavenger)[28] than in its absence (where an iodine tint is clearly visible). Ditin should also be a excellent scavenger of iodine atoms. Thus, we consider that mechanisms based on reversible addition of iodine radicals to the alkene products are unlikely when ditin is present. Third, isomerization by reversible iodine transfer may be occurring. Reversible iodide transfer is a known phenomenon for alkyl radicals,[29] and the rate measurements (eq 2) showed that the representative product **2c** was a comparable iodine donor to an alkyl iodide. Eq 4 shows how reversible iodine transfer can lead to E/Z equilibration. The observation that isomerization occurs faster when **2c** is irradiated in pure form than under the reaction conditions also supports this mechanism; *tert*-butyl iodide is a better iodine donor than a 1°- or 2°- iodide (or **2c**) and it will serve to "buffer"[30] the isomerization of vinyl iodides **2c** formed under the standard reaction conditions (newly formed radicals will abstract iodine from *tert*-butyl iodide rather than from **2c**).

17Z 15 15 17E/Z eq 4

The kinetic atom abstraction reactions of ester-substituted vinyl radicals are usually interpreted in terms of the rapidly inverting vinyl radical model.[31] Unfortunately, the lack of precise information about the kinetic product distributions of our iodides complicates somewhat the interpretation of our trends. However, the trends themselves are quite simple: compared to 1°- and 2°-iodides, 3°-iodides give initially higher levels of E-selectivity and show a better ability to retain this E-selectivity during the reaction. Qualitatively, these trends are very similar to those observed in hydrogen transfers from tin hydride (an irreversible, exothermic atom transfer).[31a]

In contrast to additions to phenyl- and ester-substituted alkynes, additions to phenylsulfonyl acetylene show a striking Z-selectivity. Furthermore, this selectivity is essentially constant throughout the course of the reaction. In contrast to the other activating groups, the phenylsulfonyl group is not a good radical stabilizing group.[32] Thus, we suspect that the final E/Z ratios are kinetically controlled. We suggest that the phenylsulfonyl-substituted vinyl radical is highly pyramidalized because the phenylsulfonyl group cannot stabilize a radical by resonance, and because electronegative groups are known to pyramidalize radicals.[33] But why do phenylsulfonyl substituted vinyl radicals behave so differently from their other vinyl radical counterparts?

Lacking quantitative knowledge of either rate constants or equilibrium constants, it is often difficult to make qualitative rationalizations in a Curtin-Hammet kinetic scenario like that in Scheme 2b. This is especially true when substituents are expected to shift the equilibrium constant (K, in Scheme 2b) and the rate constants (k_Z/k_E) in opposite directions. For ester and alkyl-substituted vinyl radicals, as the size of R increases, the kinetic selectivity in rapid atom transfers (like H transfer from tin hydride or iodine transfers) increases in favor of the E isomer.[31] Clearly, as the size of the R-group increases, the equilibrium constant should shift in favor of the trans radical (which produces the Z product). The results then indicate that this equilibrium trend is offset by an increase in the ratio of rate constants k_E/k_Z. However, such a rationale is difficult to accept, especially in the case of β-*t*-butyl substituted radicals. Given that atom transfer to **15** trans is rapid, exothermic, and provides the most stable product **17Z**, could k_Z possibly be the several orders of magnitude slower than k_E that is required to offset the equilibrium constant bias for **15** trans? Further, why do the phenylsulfonyl substituted radicals, which should also have a large equilibrium constant bias in favor of the trans-radical, give opposite selectivity?

We can escape from this quandary if we modify the structure of radical **15**-cis. For the cis-vinyl radical, the magnitude of the angle θ can be significantly larger than 120°. In the extreme, the angle θ might even reach 180°, and radical **15**-trans would then be in equilibrium with **15**-linear rather than **15**-cis. Since the barrier to interconversion of vinyl radicals is so low, it is not difficult to believe that significant steric repulsion between E and R could raise the energy of significantly bent ($\theta \ll 180°$) conformers above that of near-linear conformers ($\theta \approx 180°$).

Now reconsider the stereochemical trend for ester- and alkyl-substituted vinyl radicals in light of this proposal. As we increase the size of R, it is no longer obvious that the equilibrium constant dramatically shifts in favor of **15**-trans. Angle θ in **15**-cis simply opens with only a small sacrifice in energy to offset the steric repulsion. As the size of R increases, then the rate of iodine transfer to **15**-trans decreases.

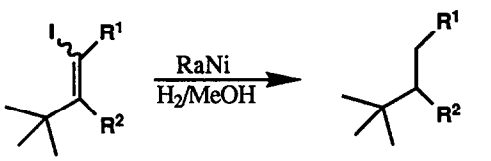
However, as the angle θ opens, the rate of iodine transfer to **15**-cis may not significantly decrease. In the extreme, **15**-cis became **15**-linear (θ = 180°C), and it is no longer obvious that this isomer must yield only **17E**. However, it is already known that linear radicals with large R groups show E-selectivity in atom transfer reactions (see Scheme 2a).

The trend with phenylsulfonyl-substituted vinyl radicals is also easily understood. The electronegativity of the $PhSO_2$ group enforces pyramidality on the radical, and thus isomer **15**-linear is raised in energy. Isomer **15**-cis strongly destabilized by steric interactions, so now there really is a large equilibrium constant bias in favor of **15**-trans. This bias is so large that, even though k_E may be greater than k_Z, there is simply not enough **15**-cis present to produce significant amounts of **17E**.

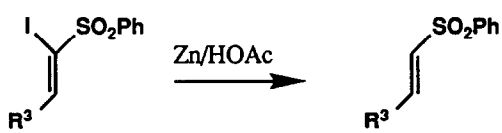
Synthetic Applications: We believe that this type of atom transfer addition reaction will be useful in synthesis. However, with the exception of some standard reductions, the few applications that we have tried to date have not been especially successful. We summarize our synthetic studies briefly below. The unsuccessful results provide some useful information on potential limitations of the method.

Treatment of vinyl iodides **2c**, **8c**, and **10c** with Raney nickel in methanol under a hydrogen atmosphere for 1-2 d (Scheme 3) resulted in hydrogenolytic cleavage of the carbon-iodine bond and hydrogenation of the alkene to give products **22**-**24** in reasonable yields (the low yield for **22** is probably due to its volatility). Although we did not stop the reactions at partial conversion, GC analysis implied that hydrogenolytic cleavage of the C–I bond was faster than hydrogenation. Clean reductive deiodination of the iodovinyl sulfones **9b** and **9c** to E-vinylsulphones **25b** and **25c** was accomplished by reduction with Zn in acetic acid, following the procedure of Truce.[34]

Scheme 3



2c	$R^1 = CO_2Me$, $R^2 = H$	**22**	38%
8c	$R^1 = R^2 = CO_2Me$	**23**	53%
10c	$R^1 = SO_2Ph$, $R^2 = H$	**24**	86%

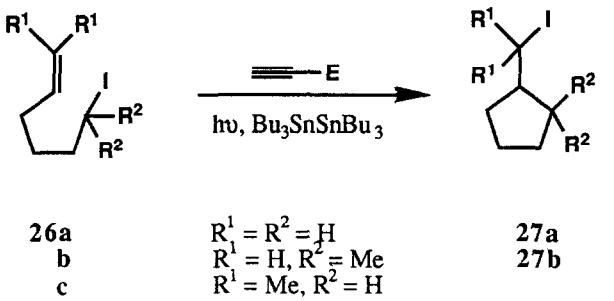


10b	$R^3 = i$-pro	**25b**
10c	$R^3 = t$-Bu	**25c**

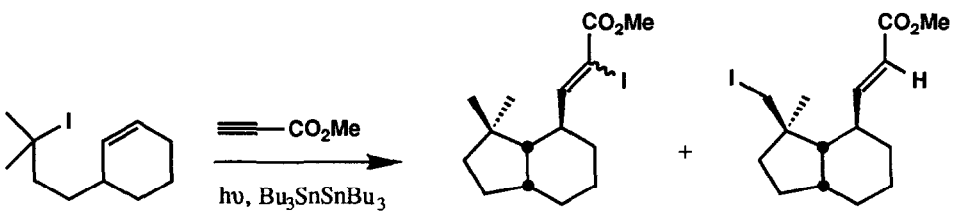
Attempts to sequence a radical cyclization prior to the addition are summarized in Scheme 4. When iodides **26a,b** were irradiated under the standard reaction conditions with methyl propiolate, we observed only products of atom transfer cyclization **27a,b**. Under these conditions, the cyclic 1°-alkyl radical abstracts iodine from the starting iodide more rapidly than it adds to methyl propiolate.[29] With iodide

26c and phenylsulfonyl acetylene as an acceptor, a chain would not propagate, and neither starting material was consumed. We did isolate some tandem addition/cyclization products from the reaction of **28** and methyl propiolate. The major product was the expected vinyl iodide **29** (E/Z mixture, 14% yield), while the minor product (single isomer, 6% yield) was tentatively assigned structure **30**. This product results from hydrogen transfer, and the stereochemistry of the iodomethyl group was assigned by assuming that this transfer was intramolecular (a 1,6-hydrogen transfer).

Scheme 4

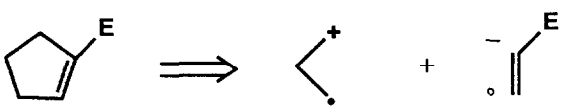


26a $R^1 = R^2 = H$ **27a**
b $R^1 = H, R^2 = Me$ **27b**
c $R^1 = Me, R^2 = H$



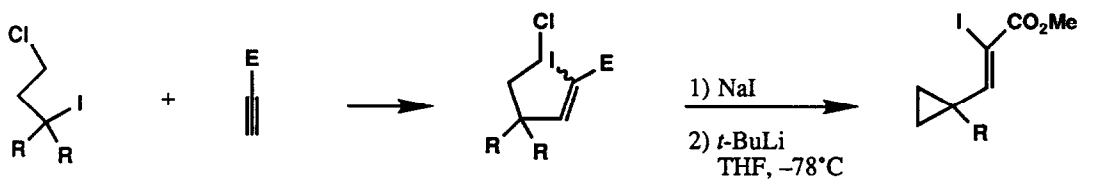
28 **29** **30**

We suspected that problems with hydrogen atom transfer again arose when we attempted to implement the annulation strategy outlined in eq 5.[35] As outlined in Scheme 5, additions of dihalides **31a** or **31b** to methyl propiolate or phenylsulfonyl acetylene gave adducts (**32a,b**, and **32a,b**) in low yields with the usual stereochemical trends. We attempted only one cyclization experiment (**32a**), with the remarkable result that cyclopropane **34** was formed in 71% yield. The low yields with the 1°-iodide **31** were expected, but the low yields with the 3°-iodide **31b** were not.



eq 5

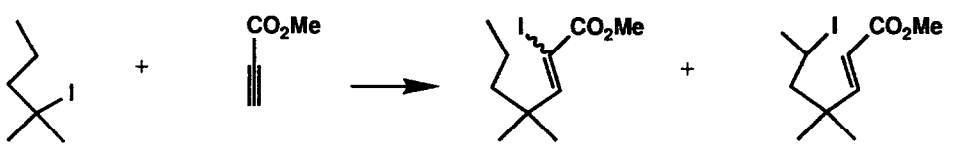
Scheme 5



			Yield (E/Z)	
31a R = H	E = CO_2Me,	**32a** E = CO_2Me	13% (33/67)	**34**
31b R = CH_3	SO_2Ph	**32a** E = SO_2Ph	25% (3/97)	
		33b E = CO_2Me	26% (84/16)	
		33b E = SO_2Ph	20% (Z-only)	

We suspected that intramolecular 1,5-hydrogen atom transfer might be a partial cause of the low yields in the addition in Scheme 5, although we did not isolate any products that we could attribute to this reaction. Evidence that this suspicion was indeed correct came from the reaction of 3°-iodide **35** and methyl propiolate under the standard conditions (Scheme 6). We isolated a separable mixture of adducts (44% yield) that contained about equal amounts of vinyl iodide **36** (E/Z mixture) and alkyl iodide **37** (exclusively E). Alkyl iodide **37** must result from an intramolecular 1,5-hydrogen transfer. Thus, in this reaction, as in other reactions of vinyl radicals, intramolecular hydrogen transfer can be a serious side reaction.[36]

Scheme 6



35 **36** **37**

Experimental

(E)- and (Z)-2-Iodo-2-heptynoic acid, methyl ester (2a).

The General Procedure: To a mixture of *n*-BuI (843.8 mg, 4.59 mmol), methyl propiolate (154.2 mg, 1.83 mmol), and hexabutylditin (266.8 mg, 0.46 mmol) in a 10mm pyrex NMR tube was added degassed benzene (2 mL). The solution was irradiated with GE-275w sunlamp at 80~85°C for 30 min. The temperature refers to the external temperature at the same distance from the sunlamp. After concentration, the residue was purified by flash chromatography (hexanes/EtOAc = 30/1) to give **2a (70 mg, 14%)** as a separable 1/2.4 mixture of E- and Z-isomers. The **2aE** eluted slightly ahead of **2aZ**: ^1H NMR ($CDCl_3$) **2aE** δ 6.92 (1H, t, J = 7.7 Hz), 3.79 (3H, s), 2.47 (2H, q, J = 7.3 Hz), 1.58–1.35 (4H, m), 0.88 (3H, t, J = 7.2 Hz); **2aZ** δ 7.22 (1H, t, J = 7.0 Hz), 3.82 (3H, s), 2.32 (2H, q, J = 7.2 Hz), 1.53-1.35 (4H, m), 0.93 (3H, t, J = 7.2 Hz); IR (thin film) **2aE** 2955, 2928, 2858, 1717, 1605, 1456, 1433, 1350, 1221, 1034, 868 cm^{-1}; **2aZ** 2955, 2928, 2858, 1717, 1615, 1456, 1435, 1250, 1132, 882 cm^{-1}; MS *m/e* 268 (M^+), 141 ($M^+ - I$); HRMS calcd. for $C_8H_{13}IO_2$: 267.9960; found: 267.9960.

(E)- and (Z)-2-Iodo-4-methyl-2-pentenoic acid, methyl ester (2b).

By the general procedure, **2b** was prepared with isopropyl iodide (271.5 mg, 1.60 mmol), methyl propiolate (53.7 mg, 0.64 mmol), and hexabutylditin (92.6 mg, 0.16 mmol) in benzene (1 mL) as a 1/2.4 mixture of E- and Z-isomers. After purification by flash chromatography (hexanes/EtOAc = 30/1), a separable E/Z-mixture of **2b** (113.8 mg, 70%) was obtained as a clear oil. The **2bE** eluted slightly ahead of **2bZ**: ^{1}H NMR ($CDCl_3$) **2bE** δ 6.70 (1H, d, J = 10.1 Hz), 3.79 (3H, s), 3.13 (1H, m), 1.02 (6H, d, J = 6.6 Hz); **2bZ** δ 6.98 (1H, d, J = 9.1 Hz), 3.81 (3H, s), 2.70 (1H, m), 1.08 (6H, d, J = 6.7 Hz); IR (thin film) **2bE** 2961, 2870, 1717, 1617, 1456, 1435, 1352, 1221, 1143, 1009, 750 cm^{-1}; **2bZ** 2963, 2870, 1717, 1615, 1456, 1435, 1246, 1142, 1030, 750 cm^{-1}; MS *m/e* 254 (M^+), 239 ($M^+ - CH_3$), 127 ($M^+ - I$); HRMS calcd. for $C_7H_{11}IO_2$: 253.9804; found: 253.9706.

(E)- and (Z)-4,4-Dimethyl-2-iodo-2-pentenoic acid, methyl ester (2c).

By the general procedure, **2c** was prepared with *t*-BuI (834.0 mg, 4.53 mmol), methyl propiolate (152.4 mg, 1.81 mmol), and hexabutylditin (262.9 mg, 0.45 mmol) in benzene (2 mL) as a 4/1 mixture of **2cE/Z** isomers. After purification by flash chromatography (hexanes/EtOAc = 30/1), an inseparable mixture of **2cE/Z** (341.5 mg, 70%) was obtained as a clear oil: ^{1}H NMR ($CDCl_3$) **2cE** δ 6.36 (1H, s), 3.78 (3H, s), 1.09 (9H, s); **2cZ** δ 7.65 (1H, s), 3.81 (3H, s), 1.27 (9H, s); IR (thin film, E,Z-mixture) 2957, 2870, 1728, 1653, 1636, 1617, 1458, 1433, 1223, 1196, 1005, 747 cm^{-1}; MS *m/e* 268, 253, 237, 221, 141, 109; HRMS calcd. for $C_8H_{13}IO_2$: 267.9960; found: 267.9960.

(E)- and (Z)-2-Iodo-4-methyl-2-pentenoic acid, ethyl ester (4b).

By the general procedure, **4b** was prepared with isopropyl iodide (515.3 mg, 3.03 mmol), ethyl propiolate (118.9 mg, 1.21 mmol), and hexabutylditin (175.8 mg, 0.303 mmol) in benzene (2 mL) as a 1/2.9 mixture of E- and Z-isomers. After purification by flash chromatography (hexanes/EtOAc = 30/1), an inseparable mixture of **4bE/Z** (256.9 mg, 79%) was obtained as a clear oil: ^{1}H NMR (C_6D_6, mixture) **4bE** δ 6.50 (1H, d, J = 10.0 Hz), 3.88 (2H, q, J = 7.1 Hz), 3.17 (1H, m), 0.89 (3H, t, J = 7.2 Hz, overlapped with Z-isomer), 0.74 (6H, d, J = 6.6 Hz, overlapped with Z-isomer); **4bZ** δ 7.00 (1H, d, J = 9.1 Hz), 3.95 (2H, q, J = 7.1 Hz), 2.62 (1H, m), 0.89 (3H, t, J = 7.2 Hz), 0.74 (6H, d, J = 6.6 Hz); IR (thin film, mixture) 2965, 2934, 2870, 1722, 1716, 1613, 1466, 1447, 1366, 1299, 1242, 1218 cm^{-1}; MS *m/e* 268 (M^+), 240, 223, 202, 128, 112, 95; HRMS calcd. for $C_8H_{13}IO_2$: 267.9960; found: 267.9960.

(E)- and (Z)-4,4-Dimethyl-2-iodo-2-pentenoic acid, ethyl ester (4c).

By the general procedure, **4c** was prepared with *t*-BuI (643.8 mg, 3.50 mmol), ethyl propiolate (137.3 mg, 1.40 mmol), and hexabutylditin (203.0 mg, 0.35 mmol) in benzene (2.5 mL) as a 2.4/1 mixture of **4cE/Z**. After purification by flash chromatography (hexanes/EtOAc = 30/1), an inseparable, mixture of **4cE/Z** (316.4 mg, 80%) was obtained as a clear oil: ^{1}H NMR ($CDCl_3$, mixture) **4cE** δ 6.33 (1H, s), 4.23 (2H, q, J = 7.1 Hz), 1.32 (3H, t, J = 7.1 Hz, overlapped with Z-isomer), 1.10 (9 H, s); **4cZ** δ 7.63 (1H, s), 4.25 (2H, q, J = 7.1 Hz), 1.32 (3H, t, J = 7.1 Hz), 1.27 (9H, s); IR (thin film, E,Z-mixture) 2961, 2906, 2871, 1725, 1617, 1601, 1464, 1447, 1367, 1315, 1120, 1093, 1027 cm^{-1}; MS *m/e* 282, 267, 239, 232, 213, 187, 143, 109; HRMS calcd. for $C_9H_{15}IO_2$: 282.0117; found: 282 0117.

(E)- and (Z)-(1-Iodo–1-hexenyl)benzene (6a).

By the general procedure, **6a** was prepared with *n*-BuI (203.1 mg, 1.10 mmol), phenylacetylene (45.1 mg, 0.44 mmol), and hexabutylditin (64.0 mg, 0.11 mmol) in benzene (1 mL). After purification by flash chromatography (100% hexanes), **6a** (23.8 mg, 19%) was obtained as an inseparable 1/1.5 mixture of E- and Z-isomers: ^{1}H NMR ($CDCl_3$, mixture) **6aE** δ 7.50-7.10 (5H, m), 6.46 (1H, t, J = 7.7 Hz), 2.20 (2H, m), 1.51-1.15 (4H, m), 0.82 (3H, t, J = 7.1 Hz); **6aZ** δ 7.50-7.10 (5H, m), 5.89 (1H, t, J = 7.7 Hz), 2.30 (2H, m), 1.51-1.15 (4H, m), 0.95 (3H, t, J = 7.1 Hz); IR (thin film, mixture) 3056, 3023, 2955, 2926, 2857, 1653, 1636, 1617, 1456, 1443, 1377, 754 cm^{-1}; MS *m/e* 286 (M^+), 229 ($M^+ - C_4H_9$), 159 ($M^+ - I$); HRMS calcd. for $C_{12}H_{15}I$: 286.0219; found: 286.0202.

(E)- and (Z)-(1-Iodo-3-methyl-1-butenyl)benzene (6b).

By the general procedure, **6b** was prepared with isopropyl iodide (111.6 mg, 1.13 mmol), phenylacetylene (46.0 mg, 0.45 mmol), and hexabutylditin (65.4 mg, 0.11 mmol) in benzene (1 mL). After purification by flash chromatography (100% pentanes), **6b** (69.1 mg, 56%) was obtained as an inseparable 1/2.9 mixture of E- and Z-

isomers: ^{1}H NMR ($CDCl_3$, mixture) **6bE** δ 7.45-7.23 (5H, m), 6.29 (1H, d, J = 10.3 Hz), 2.33 (1H, m), 0.95 (6H d, J = 6.6 Hz); **6bZ** δ 7.45-7.23 (5H, m), 5.67 (1H, d, J = 8.5 Hz), 2.71 (1H, m), 1.10 (6H, d, J = 6.7 Hz); IR (thir film, mixture) 3070, 3063, 2959, 2926, 2866, 1647, 1634, 1617, 1489, 1456, 1443, 756 cm^{-1}; MS, *m/e* 272 (M^+) 145 ($M^+ - I$); HRMS: calcd. for $C_{11}H_{13}I$: 272.0062; found: 272.0061.

(E)- and (Z)-(3,3-Dimethyl-1-iodo-1-butenyl)benzene (6c).

By the general procedure, **6c** was prepared with *t*-BuI (197.7 mg, 1.07 mmol), phenylacetylene (43.9 mg, 0.43 mmol), and hexabutylditin (62.1 mg, 0.11 mmol) in benzene (1 mL). After flash chromatography (100% pentanes), **6c** (73.3 mg, 60%) was obtained as an inseparable 2.8/1 mixture of E- and Z-isomers: ^{1}H NMR ($CDCl_3$, mixture) **6cE** δ 7.39-7.20 (5H, m), 6.46 (1H, s), 0.97 (9H, s); **6cZ** δ 7.39-7.20 (5H, m), 6.22 (1H, s), 1.27 (9H, s); IR (thin film mixture) 3058, 2959, 2901, 2866, 1630, 1593, 1475, 1362, 1200, 1028, 831 cm^{-1}; MS *m/e* 286 (M^+), 229 ($M^+ - C_4H_9$), 159 ($M^+ - I$); HRMS calcd. for $C_{12}H_{15}I$: 286.0219; found: 286.0198.

(E)- and (Z)-(1-Iodo-3-phenyl-1-propenyl)benzene (6d).

By the general procedure, **6d** was prepared with benzyl iodide (743.4 mg, 3.41 mmol), phenylacetylene (139.3 mg 1.36 mmol), and hexabutylditin (197.8 mg, 0.34 mmol) in benzene (2 mL). After flash chromatography (100% hexanes), **6d** (154.0 mg, 35%) was obtained as an inseparable 1.4/1 mixture of E- and Z-isomers: ^{1}H NMR ($CDCl_3$ mixture) **6dE** δ 7.50-7.10 (10H, m), 6.65 (1H, t, J = 7.8 Hz), 3.31 (2H, d, J = 7.8 Hz); **6dZ** δ 7.50-7.10 (10 H, m) 6.08 (1H, t, J = 6.9 Hz), 3.69 (2H, d, J = 6.9 Hz); IR (thin film, mixture) 3062, 3027, 2927, 1645, 1606, 1495 1450, 1215, 1177, 1000 cm^{-1}; MS *m/e* 320 (M^+), 193 ($M^+ - I$); HRMS calcd. for $C_{15}H_{13}I$: 320.0062; found 320.0062.

(E)- and (Z)-2-Iodo-3-(1-methylethyl)-2-butenedioic acid, dimethyl ester (8b).

By the general procedure, **8b** was prepared with isopropyl iodide (164.5 mg, 0.97 mmol), dimethyl acetylene dicarboxylate (55.0 mg, 0.39 mmol), and hexabutylditin (56.1 mg, 0.097 mmol) in benzene (1 mL) as a 4.6/1 mixture of E- and Z-isomers. After flash chromatography (pentanes/EtOAc = 20/1), a separable E/Z-mixture of **8b** (98.2 mg 81%) was obtained as a clear oil. Isomer **8bZ** eluted slightly ahead of **8bE**: ^{1}H NMR ($CDCl_3$) **8bE** δ 3.81 (3H, s) 3.78 (3H, s), 2.97 (1H, m), 1.15 (6H, d, J = 6.9 Hz); **8bZ** δ 3.85 (3H, s), 3.83 (3H, s), 3.18 (1H, m), 1.13 (6H, d J = 6.9 Hz); IR (thin film) **8bE** 2953, 1732, 1592, 1456, 1435, 1250, 1194, 1174, 1143, 768 cm^{-1}; **8bZ** 2955, 1730 1607, 1433, 1366, 1239, 1194, 1144, 1042, 1009, 882 cm^{-1}; MS *m/e* 312 (M^+), 253 ($M^+ - CO_2Me$), 185 ($M^+ - I$) 126 ($M^+ - CO_2Me - I$); HRMS calcd. for $C_9H_{13}IO_4$: 311.9859; found: 311.9859.

(E)- and (Z)-3-(1,1-Dimethylethyl)-2-iodo-2-butenedioic acid, dimethyl ester (8c).

By the general procedure, **8c** was prepared with *t*-BuI (558.8 mg, 3.04 mmol), DMAD (172.6 mg, 1.21 mmol), and hexabutylditin (176.1 mg, 0.30 mmol) in benzene (2 mL) as a 1/3.2 mixture of E- and Z-isomers. After flash chromatography (pentanes/EtOAc = 20/1), a separable E/Z-mixture of **8c** (237.3 mg, 60%) was obtained as a viscous oil. Isomer **8cZ** eluted slightly ahead of **8cE**: ^{1}H NMR ($CDCl_3$) **8cE** δ 3.83 (3H, s), 3.82 (3H, s), 1.21 (9H, s); **8cZ** δ 3.78 (3H, s), 3.77 (3H, s), 1.39 (9H, s); IR (thin film) **8cE**: 2953, 1732, 1617, 1433, 1399, 1236, 1064, 1035, 889 cm^{-1}; **8cZ**: 2953, 2872, 1734, 1570, 1433, 1397, 1366, 1246, 1069, 1011, 967, 820 cm^{-1}; MS *m/e* 326 (M^+), 311 ($M^+ - CH_3$), 267 ($M^+ - CO_2Me$), 140 ($M^+ - CO_2Me - I$); HRMS calcd. for $C_{10}H_{15}IO_4$: 326.0015; found: 326.0016.

(E)- and (Z)-((1-Iodo-1-hexenyl)sulfonyl)benzene (10a).

By the general procedure, **10a** was prepared with *n*-BuI (196.8 mg, 1.07 mmol), ethynyl phenyl sulfone (71.1 mg, 0.43 mmol), and hexabutylditin (62.1 mg, 0.107 mmol) in benzene (1 mL). After purification by flash chromatography (hexanes/EtOAc = 30/1), **10a** (26.7 mg, 18%) was obtained as an inseparable 1/14 mixture of E- and Z-isomers: ^{1}H NMR($CDCl_3$, E/Z-mixture) **10aE** δ 7.93~7.55 (5H, m), 6.98 (1H, t, J = 7.3 Hz), 2.75 (2H, q, J = 7.4 Hz), 1.60-0.80 (7H, m, overlapped with Z); **10aZ** δ 7.93-7.55 (5H, m), 7.36 (1H, t, J = 7.0 Hz), 2.29 (2H, q, J = 7.4 Hz), 1.53 (2H, m), 1.38 (2H, m), 0.93 (3H, t, J = 7.3 Hz); IR (thin film) **10aZ** 3063, 2957, 2928, 2861, 1595, 1446, 1379, 1319, 1307, 1153, 1086 cm^{-1}; MS *m/e* 350 (M^+), 223 ($M^+ - I$); HRMS calcd. for $C_{12}H_{15}IO_2S$: 349.9838; found: 349.9836.

(E)- and (Z)-((1-Iodo-3-methyl-1-butenyl)sulfonyl)benzene (10b).

By the general procedure, **10b** was prepared with isopropyl iodide (141.4 mg, 0.83 mmol), ethynyl phenyl sulfone (55.3 mg, 0.33 mmol), and hexabutylditin (48.3 mg, 0.083 mmol) in benzene (1 mL). After flash chromatography (hexanes/EtOAc = 6/1), **10b** (68.2 mg, 61%) was obtained as a 1/17 mixture of E- and Z-isomers. Recrystallization in ethanol gave pure crystals of **10bZ** for X-ray analysis, mp 120.5-121.5°C; ^{1}H NMR ($CDCl_3$) **10bE** (taken from E,Z-mixture before recrystallization) δ 7.93-7.52 (5H, m), 6.76 (1H, d, J = 9.0 Hz), 2.60 (1H, m), 1.01 (6H, d, J = 6.7 Hz); **10bZ** δ 7.93-7.55 (5H, m), 7.16 (1H, d, J = 9.1 Hz), 2.60 (1H, m), 1.11 (6H, d, J = 6.6 Hz); IR (thin film, mixture) 2965, 2868, 1593, 1447, 1364, 1304, 1140 cm^{-1}; MS *m/e* 336 (M^+), 209 ($M^+ - I$); HRMS calcd. for $C_{11}H_{13}IO_2S$: 335.9681; found: 335.9667.

(Z)-((3,3-Dimethyl-1-iodo-1-butenyl)sulfonyl)benzene (10c).

By the general procedure, **10c** was prepared with *t*-BuI (154.2 mg, 0.84 mmol), ethynyl phenyl sulfone (55.7 mg, 0.34 mmol), and hexabutylditin (48.6 mg, 0.084 mmol) in benzene (1 mL). After purification by flash chromatography (hexanes/EtOAc = 6/1), pure **10cZ** (97.4 mg, 83%) was obtained as a white solid. Recrystallization in ethanol gave pure crystals of the Z-isomer for X-ray analysis, mp 140-142°C: ^{1}H NMR ($CDCl_3$) **10cZ** δ 7.91 (2H, m), 7.82 (1H, s), 7.65~7.55 (3H, m), 1.26 (9H, s); IR (thin film) 2980, 2961, 2930, 2872, 1595, 1449, 1362, 1296, 1146 cm^{-1}; MS *m/e* 350 (M^+), 335 ($M^+ - CH_3$), 223 ($M^+ - I$); HRMS calcd. for $C_{12}H_{15}IO_2S$: 349.9838; found: 349.9820

(E)- and (Z)-5-Iodo-5-decene (12a).

A solution of *n*-BuI (193.5 mg, 1.05 mmol), 1-hexyne (34.8 mg, 0.42 mmol), and hexabutylditin (61.0 mg, 0.11 mmol) in benzene (1 mL) was irradiated with a sunlamp in a sealed tube for 30 min at ~180°C. The temperature refers to the external temperature. After purification by flash chromatography (100% pentanes), **23** (14.6 mg, 13%) was obtained as an inseparable 1/3 mixture of E- and Z-isomers: ^{1}H NMR ($CDCl_3$, mixture) **12aE** 6.17 (1H, t, J = 7.5 Hz), 2.37 (2H, t, J = 7.4 Hz), 2.05 (2H, m), 1.55-1.10 (8H, m), 0.96-0.76 (6H, m); **12aZ** δ 5.46 (1H, t, J = 7.5 Hz), 2.45 (2H, t, J = 7.3 Hz), 2.10 (2H, m), 1.55-1.10 (8H, m), 0.96-0.76 (6H, m); IR (thin film, mixture) 2957, 2926, 2870, 2859, 1646, 1464, 1377, 1136 cm^{-1}; MS *m/e* 266 (M^+), 209 ($M^+ - C_4H_9$), 139 ($M^+ - I$); HRMS calcd. for $C_{10}H_{19}I$. 266.0532; found: 266.0531.

(E)- and (Z)-4-Iodo-2-methyl-3-octene (12b).

According to the procedure for the preparation of **12a**, **12b** was prepared with isopropyl iodide (134.0 mg, 0.79 mmol), 1-hexyne (26.1 mg, 0.32 mmol), and hexabutylditin (45.8 mg, 0.079 mmol) in benzene (1 mL). After purification by flash chromatography (100% pentanes), **12b** (31.5 mg, 39%) was obtained as an inseparable 1/2.4 mixture of E- and Z-isomers: ^{1}H NMR ($CDCl_3$, mixture) **12bE** δ 6.00 (1H, d, J = 8.5 Hz,), 2.62-2.35 (3H, m), 1.50 (2H, m), 1.30 (2H, m), 0.99 (6H, d, J = 6.7 Hz), 0.95-0.83 (3H, m); **12bZ** δ 5.24 (1H, d, J = 8.4 Hz,), 2.62-2.35 (3H, m), 1.50 (2H, m), 1.30 (2H, m), 0.99 (6H, d, J = 6.7 Hz), 0.95-0.83 (3H, m); IR (thin film, mixture) 2959, 2930, 2869, 1640, 1464, 1381, 1362, 1150, 949, 837 cm^{-1}; MS *m/e* 252 (M^+), 125 ($M^+ - I$); HRMS calcd. for $C_9H_{17}I$: 252.0375; found: 252.0376.

(E)- and (Z)-2,2-Dimethyl-4-iodo-3-octene (12c).

By the general procedure, **12c** was prepared with *t*-BuI (582.1 mg, 3.16 mmol), 1-hexyne (104.7 mg, 1.27 mmol), and hexabutylditin (183.5 mg, 0.32 mmol) in benzene (2 mL). After purification by flash chromatography (100% hexanes), **12c** (75.4 mg, 22%) was obtained as an inseparable 3/1 mixture of E- and Z-isomers: ^{1}H NMR ($CDCl_3$, mixture) **12cE** δ 6.23 (1H, s), 2.45 (2H, m), 1.65-1.20 (4H, m), 1.12 (H, s), 1.0-0.85 (3H, m); **12cZ** δ 5.88 (1H, s), 2.45 (2H, m), 1.65-1.20 (4H, m), 1.17 (9H, s), 1.0-0.85 (3H, m); IR (thin film, mixture) 2957, 2926, 2870, 1653, 1636, 1617, 1522, 1456, 1364, 1244, 1109, 1075 cm^{-1}; MS *m/e* 266 (M^+), 139 ($M^+ - I$); HRMS calcd. for $C_{10}H_{19}I$: 266.0532; found: 266.0530.

4,4-Dimethyl-pentanoic acid, methyl ester (22).

To a solution of the vinyl iodide **2c** (77.3 mg, 0.29 mmol) in methyl alcohol (1 mL) was added Raney-Nickel (2 spatula tips). The mixture was stirred for 48 h at 25°C. Filtration, concentration, and purification by flash chromatography (hexanes/EtOAc = 10/1) gave **29** (14.1 mg, 38%) as a clear oil: ^{1}H NMR ($CDCl_3$) δ 3.67 (3H, s)

2.29 (2H, m), 1.55 (2H, m), 0.90 (9H, s); IR (thin film) 2957, 2926, 1734, 1456, 1367 cm^{-1}; MS *m/e* 129 ($M^+ - CH_3$), 70 ($M^+ - CH_3 - CO_2Me$); HRMS calcd. for $C_7H_{13}O_2$ ($M^+ - CH_3$): 129.0916; found: 129.0916.

2-(1,1-Dimethylethyl)-butanedioic acid, dimethyl ester (23).

By the same procedure for the preparation of **22**, vinyl iodide **8c** (24.6 mg, 0.075 mmol) was converted to **23** (18 mg, 53%) as a slightly yellow oil: ^1H NMR ($CDCl_3$) δ 3.70 (3H, s), 3.66 (3H, s), 2.85-2.45 (3H, m), 0.96 (9H, s); IR (thin film) 2957, 1738, 1456, 1437, 1371, 1211, 1159 cm^{-1}; MS *m/e* 171($M^+ - OCH_3$), 114 ($M^+ - OCH_3 - C_4H_9$); HRMS calcd. for $C_9H_{15}O_3$ ($M^+ - OCH_3$): 171.1021; found: 171.1020.

((3,3-Dimethylbutyl)sulfonyl)benzene (24).

By the same procedure for the preparation of **22**, vinyl iodide **10c** (46 mg, 0.13 mmol) was converted to **24** (25.5 mg, 86%): ^1H NMR ($CDCl_3$) δ 7.93-7.58 (5H, m), 3.07 (2H, m), 1.60 (2H, m), 0.87 (9H, s); IR (thin film) 3065, 2957, 2869, 1586, 1476, 1447, 1368, 1320, 1302, 1242, 1150, 1088 cm^{-1}; MS *m/e* 226 (M^+), 211 ($M^+ - CH_3$), 169 ($M^+ - C_4H_9$), 161 ($M^+ - Ph$); HRMS calcd. for $C_{12}H_{18}O_2S$: 226.1028; found: 226.1027.

(E)-((3-Methyl-1-butenyl)sulfonyl)benzene (25b).

To a solution of vinyl iodide **10b** (3.9 mg, 0.01 mmol) and acetic acid (0.96 mg, 0.016 mmol) in water (1 mL) was added zinc dust (0.9 mg, 0.014 mmol). The mixture was refluxed for 3 h. The product was extracted with diethyl ether (3x) and the combined organic phase was washed with saturated aqueous sodium bicarbonate (1x), water (1x), and cold brine, and dried over $MgSO_4$. Concentration gave **25b** (2.3 mg, 94%) as a slightly yellow oil: ^1H NMR ($CDCl_3$) δ 7.88-7 55 (5H, m), 6.99 (1H, dd, J = 6.3, 15.2 Hz), 6.25 (1H, dd, J = 1.5, 15.2 Hz), 2.50 (1H, m), 1.08 (6H, d, J = 6.8 Hz).

(E)-((3,3-Dimethyl-1-butenyl)sulfonyl)benzene (25c).

According to the procedure for the preparation of **25b**, **10c** (3.5 mg, 0.01 mmol) was reduced with Zn (0.8 mg, 0.012 mmol) and acetic acid (0.96 mg, 0.016 mmol) in water (1 mL) to give **25c** (2.7 mg, 100%) as the sole detectable isomer: ^1H NMR ($CDCl_3$) δ 7.88-7.54 (5H, m), 6.99 (1H, d, J = 15.3 Hz), 6.20 (1H, d, J = 15.3 Hz), 1.09 (9H, s).

7-(2-Carbomethoxy-2-iodoethenyl)-1,1-dimethyl-bicyclo[3,4,0]nonane (29).

By the general procedure, **29** was prepared with methyl propiolate (7.3 mg, 0.086 mmol), iodide **27** (28.8 mg, 0.104 mmol), and hexabutylditin (6 mg, 0.0104 mmol) in benzene (0.3 mL). After purification by flash chromatography (hexanes/EtOAc = 20/1), **28** (4.2 mg, 14%) and **29** (2.0 mg, 6%) were obtained as slightly yellow oils. The vinyl iodide **28** eluted slightly ahead of the primary iodide **29**: ^1H NMR ($CDCl_3$) δ 7.12 (1H, d, J = 8.9 Hz), 3.82 (3H, s), 2.35 (1H, m), 1.70-1.40 (12H, m), 1.00 (3H, s), 0.85 (3H, s).

7-(2-Carbomethoxyethenyl)-1-Iodomethyl-1-methyl-bicyclo[3,4,0]nonane (30).

^1H NMR ($CDCl_3$) δ 6.95 (1H, dd, J = 8.6. 15.4 Hz), 5.82 (1H, d, J = 15.4 Hz), 3.72 (3H, s), 3.35 (1H, d, J = 9.3 Hz), 3.17 (1H, d, J = 9.3 Hz), 2.28 (1H, m), 1.85-1.15 (12H, m), 1.06 (3H, s).

(E)- and (Z)-6-Chloro-2-iodo-hex-2-enoic acid, methyl ester (32a, E = CO_2Me).

By the general procedure, **32a** was prepared with primary iodide **31a** (1.96 g, 9.59 mmol), methyl propiolate (403 mg, 4.79 mmol), and hexabutylditin (556 mg, 0.96 mmol) in benzene (2 mL) as a 1/1.9 mixture of E- and Z-isomers. After purification by flash chromatography (hexanes/EtOAc = 30/1), **32a** (180.8 mg, 13%) was obtained as a clear oil. **32aE** eluted slightly ahead of **32aZ**: ^1H NMR ($CDCl_3$) **32aE** δ 6.90 (1H, t, J = 7.9 Hz), 3.80 (3H, s), 3.54 (2H, t, J = 6.6 Hz), 2.62 (2H, q, J = 7.5 Hz), 1.93 (2H, m); **32aZ** δ 7.23 (1H, t, J = 7.1 Hz), 3.83 (3H, s), 3.58 (2H, t, J = 6.5 Hz), 2.49 (2H, q, J = 7.5 Hz), 1.99 (2H, m); MS *m/e* 288 (M^+), 257, 161 ($M^+ - I$); HRMS: Calcd. for $C_7H_{10}ClIO_2$: 287.9414; found: 287.9414.

(E)- and (Z)-6-Chloro-4,4-dimethyl-2-iodo-hex-2-enoic acid, methyl ester (32b, E = CO_2Me).

By the general procedure, **32b** was prepared with iodide **31b** (493.2 mg, 2.121 mmol), methyl propiolate (99.6 mg, 1.185 mmol), and hexabutylditin (123.1 mg, 0.212 mmol) in benzene (2 mL) as a 6/1 mixture of E- and Z-isomers. After purification by flash chromatography (hexanes/EtOAc = 20/1), **32b** (96.7 mg, 26%) was obtained as a

clear oil: ^{1}H NMR ($CDCl_3$) **31bE** δ 6.26 (1H, s), 3.79 (3H, s), 3.49 (2H, t, J = 8.2 Hz), 1.87 (2H, t, J = 8.5 Hz), 1.08 (6H, s).

(E)- and (Z)-((5-Chloro-1-iodo-1-pentenyl)sulfonyl)benzene (33a, E = SO_2Ph).

By the general procedure, **33a** was prepared with the primary iodide **31a** (361.7 mg, 1.769 mmol), ethynyl phenyl sulfone (58.8 mg, 0.354 mmol), and hexabutylditin (102.6 mg, 0.177 mmol) in benzene (1 mL) as a 1/30 mixture of E- and Z-isomers. After purification by flash chromatography (hexanes/EtOAc = 30/1), **33a** (33.1 mg, 25%) was obtained as a clear oil: ^{1}H NMR ($CDCl_3$) **33aE** δ 8.0-7.35 (5H, m), 6.97 (1H, t, J = 7.1 Hz), 3.55 (2H, t, J = 6.2 Hz), 2.52-1.90 (4H, m); **33aZ** δ 8.0-7.35 (5H, m, overapped with E-isomer), 7.38 (1H, t, J = 7.1 Hz), 3.58 (2H, t, J = 6.2 Hz), 2.47 (2H, q, J = 7.5 Hz), 2.00-1.90 (2H, m).

Z-((5-Chloro-3,3-dimethyl-1-iodo-1-pentenyl)sulfonyl)benzene (33b, E = SO_2Ph).

By the general procedure, **33b** was prepared with the iodide **31b** (456.7 mg, 1.964 mmol), ethynyl phenyl sulfone (150 mg, 0.903 mmol), and hexabutylditin (114 mg, 0.196 mmol) in benzene (3 mL). After purification by flash chromatography (hexanes/EtOAc = 6/1), **33bZ** (72 mg, 20%) was obtained as a clear oil: ^{1}H NMR ($CDCl_3$) δ 7.92-7.50 (5H, m), 7.79 (1H, s), 3.43 (2H, t, J = 6.2 Hz), 2.13 (2H, t, J = 6.2 Hz), 1.28 (6H, s).

(Z)-(2-Iodo-carbomethoxyvinyl)-cyclopropane (34).

To a solution of the vinyl iodide **32aZ** (84 mg, 0.291 mmol) in acetone (10 mL) was added NaI (743 mg, 4.956 mmol) at 25°C. The mixture was refluxed for 24 h. The product was extracted with diethyl ether (3x) and the combined organic phase was washed with water and cold brine, and dried over $MgSO_4$. Concentration gave the diiodide (80.5 mg, 73%) as a slightly yellow oil: ^{1}H NMR ($CDCl_3$) δ 7.21 (1H, t, J = 7.0 Hz), 3.82 (3H, s), 3.22 (2H, t, J = 6.9 Hz), 2.44 (2H, q, J = 7.3 Hz), 2.04 (2H, m). To a solution of this diiodide (62.2 mg, 0.164 mmol) in THF (1.6 mL) was added *t*-BuLi (1.6 M, 256 μl) dropwise at –78°C. The mixture was stirred at –78°C for 45 min and at 25°C for 15 min. After the addition of water, the product was extracted with diethyl ether (3x) and the combined organic phase was washed with water and cold brine, and dried over $MgSO_4$. Concentration gave **34** (29.2 mg, 71%) as a slightly yellow oil: ^{1}H NMR ($CDCl_3$) δ 6.62 (1H, d, J = 9.9 Hz), 3.80 (3H, s), 1.90-1.70 (1H, m), 1.20-1.00 (2H, m), 0.85-0.70 (2H, m); ^{13}C NMR δ 158 (d), 88.6 (s), 53 (q), 20 (d), 9 (t); IR (thin film) 3007, 2952, 1717, 1607, 1433, 1358, 1248, 1194, 1172, 1038 cm^{-1}.

E- and Z-4,4-Dimethyl-2-iodo-hept-2-enoic acid, methyl ester (36).

By the general procedure, **36** was prepared with the 3°-iodide 113 (64 mg, 0.302 mmol), methyl propiolate (10.1 mg, 0.12 mmol), and hexabutylditin (17.5 mg, 0.03 mmol) in benzene (1 mL) as a 1/1.2 mixture of **36** and **37**. After purification by flash chromatography (hexanes/EtOAc = 20/1), **36** (7.3 mg, 20%) and **37** (8.7 mg, 24%) were obtained as clear oils. The vinyl iodide **36** eluted slightly ahead of **37**: ^{1}H NMR ($CDCl_3$) **36E** δ 6.28 (1H, s), 3.76 (3H, s), 1.75~1.00 (7H, m), 1.10 (6H, s); **36Z** δ 7.62 (1H, s), 3.70 (3H, s), 1.75~1.10 (7H, m, overlapped with E-isomer), 1.09 (6H, s).

E-4,4-Dimethyl-6-iodo-hept-2-enoic acid, methyl ester (37).

^{1}H NMR ($CDCl_3$) δ 6.97 (1H, d, J = 16.0 Hz), 5.76 (1H, d, J = 16.0 Hz), 4.16 (1H, m), 3.74 (3H, s), 2.38 (1H, dd, J = 5.7, 15.0 Hz), 2.01 (1H, dd, J = 7.08, 15.0 Hz), 1.89 (3H, d, J = 6.8 Hz), 1.14 (3H, s), 1.10 (3H, s); IR (thin film) 2961, 2924, 1724, 1653, 1435, 1368, 1314, 1167.

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36. At this point, we began to wonder if the low yields with *n*-butyl iodide might not be due to hydrogen transfer reactions. However, a few standard addition experiments with ethyl iodide also resulted in very poor yields of adducts (<20%).