

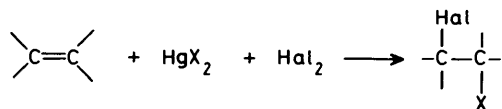
Stereoselective Bifunctionalization of Alkynes by Means of the Mercury(II) Salt-Iodine Combination

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The reaction of alkynes with iodine and mercury(II) salts (chloride, acetate, methanesulphonate, toluene-*p*-sulphonate, benzyl sulphide, toluene-*p*-sulphinic acid, and thiocyanate) affords stereoselectively *E*- β -functionalized vinyl iodides resulting from the ionic addition of iodine and the mercury(II) salt anion. Unsymmetrical alkynes yield regioselectively Markovnikov addition products. In the case of mercury(II) thiocyanate the reaction can be used also for the stereoselective preparation of *E*-1,2-dithiocyanatoalkenes. An ionic mechanism is proposed according to the observed regio- and stereochemistry.

Electrophilic additions to alkynes have been studied less than the corresponding ones to alkenes, especially for I-Nu reagents.¹ Recently we have reported that the mercury(II) salt-halogen combination $\text{HgX}_2\text{-Hal}_2$ is a versatile reagent for the bifunctionalization of alkenes.² The reaction allows the *trans*-stereoselective addition of Br-X and I-X to the double bond (Scheme 1). In the case of dienes the monoaddition product has been obtained, and when allylic derivatives were used as olefinic substrate the corresponding 1,2,3-trifunctionalized compounds were prepared.^{2b}



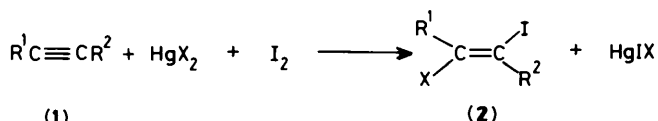
Scheme 1. Hal = Br, I; X = F, Cl, Br, RCO₂, RSO₃, RSO₂, NO₃

The mercury(II) chloride-iodine reagent is also adequate for the direct and regioselective α -iodination of carbonyl compounds.³

Continuing with our studies on the use of this type of reagent in organic synthesis we have found that the mercury(II) salt-iodine combination leads to the stereoselective and regioselective addition of I-X to alkynes.

Results and Discussion

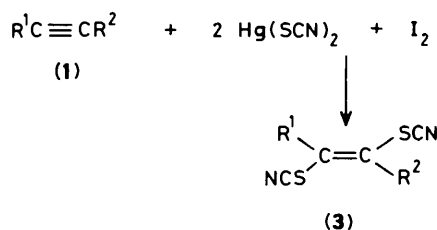
The treatment of acetylenes (1) with mercury(II) salts and iodine in dichloromethane gave the corresponding *E*- β -functionalized vinylic iodides (2) stereoselectively (Scheme 2 and Table). The reaction was carried out using 1:1:1 molar proportions of alkyne:mercury(II) salt:iodine and at 0 °C in order to avoid the formation of di-iodo derivatives. Under these reaction conditions less than 10% of *E*-1,2-di-iodoalkenes were obtained, and these were easily separated from the reaction product by chromatography.†



Scheme 2. R¹, R², and X are defined in the table

The nucleophiles incorporated are similar to those used in the addition of alkanes;² so, mercury(II) chloride, acetate, sulphonates, sulphinates, and thiocyanate were successfully em-

ployed. With alkynes it was also possible to achieve addition of benzyl sulphide to afford the product (2e). The use of mercury(II) toluene-*p*-sulphinic acid led to the expected iodovinyl sulphone (2f) resulting from the attack of the more nucleophilic sulphur atom. In the case of the addition of the thiocyanate anion we observed more selectivity for alkynes than for alkenes² since only thiocyanato derivatives were isolated and no isothiocyanato ones were detected. For the obtention of compounds (2g) and (2h) the best results were obtained when potassium thiocyanate was added (1:1 molar ratio) to the reaction mixture. However when the reaction of mercury(II) thiocyanate and iodine with alkynes was carried out with double the amount of mercury(II) salt the corresponding *E*-1,2-dithiocyanatoalkenes (3) were obtained (Scheme 3 and Table).



Scheme 3.

The addition of other nucleophiles such as bromide or nitrate,‡ observed in the case of alkenes, failed for alkynes. On the other hand the reaction with mercury(II) salts and bromine led exclusively to the corresponding dibromo derivatives.

With unsymmetrical alkynes the reaction took place regioselectively according to the stability of the intermediate vinyl carbenium ion. Terminal acetylenes reacted with mercury(II) thiocyanate to yield the corresponding addition products (2h), (3b), and (3c); however, in the case of mercury(II) chloride and acetate it was necessary to protect the terminal acetylene in order to avoid the formation of the corresponding alkynyl iodides. Thus, the iodofunctionalization of 1-phenyl-2-(trimethylsilyl)acetylene led to the chloro and acetoxy vinylic iodides (2i) and (2j).

The reaction proceeded completely in a *trans* fashion in all cases, the stereochemistry of isolated products (2) and (3) being determined by comparison of their physical (Table) and n.m.r. data (see Experimental section) with those described in the literature.⁴⁻⁸ The observed stereoselectivity in the preparation

† Using a short column of silica gel, and hexane as eluant.

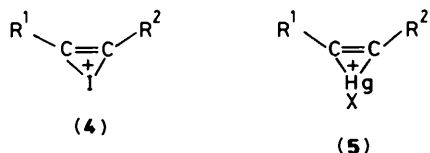
‡ The addition of I-NO₃ to alkynes also fails (U. E. Diner and J. W. Lown, *Can. J. Chem.*, 1971, **49**, 403).

Table. Preparation of compounds (2) and (3)

Product	R ¹	R ²	X	Reaction time	Yield (%) ^a	B.p. (°C/mmHg), ^b or m.p. (°C), or R _f ^c	Lit. b.p.(°C/mmHg) or m.p. (°C)
(2a)	Et	Et	Cl	1.5 h	62	78—78/15	78—80/19 ⁴
(2b)	Et	Et	AcO	3 h	71	96—98/15	
(2c)	Et	Et	MeSO ₃	4 h	60	0.20	
(2d)	Et	Et	<i>p</i> -MeC ₆ H ₄ SO ₃	1 h	35	0.35	
(2e)	Et	Et	PhCH ₂ S	16 h	35 ^d	0.57	
(2f)	Et	Et	<i>p</i> -MeC ₆ H ₄ S(O) ₂ [*]	1 h	78	65—67 ^e	66—67 ⁵
(2g)	Et	Et	NCS	20 h	40 ^{f,g}	0.53	
(2h)	Bu ⁿ	H	NCS	3 h	45 ^{f,h}	0.61 ⁱ	
(2i)	Ph	Me ₃ Si	Cl	2 h	54	0.58	
(2j)	Ph	Me ₃ Si	AcO	2 h	50	0.53	
(2k)	Ph	Me	Cl	1.5 h	69	49—53/0.1	94—96/2 ⁴
(2l)	Ph	Me	AcO	1 h	50	86—88/0.1	114—116/4 ⁶
(2m)	Ph	Ph	AcO	24 h	48	145—146 ^j	146—146.5 ⁷
(3a)	Et	Et		3 h	92 ^k	0.30 ⁱ	oily solid ⁸
(3b)	Bu ⁿ	H		1 h	89 ^l	0.39 ⁱ	liquid ⁸
(3c)	Ph	H		14 h	68 ^m	68—69 ⁿ	68—69 ⁸

^a Isolated yield based on the starting amount of alkyne (1). ^b Distillation temperature range. ^c Silica gel, hexane–ether (4:1). ^d Benzyl disulphide (ca. 30%) was also isolated. ^e From hexane–chloroform. ^f Potassium thiocyanate (1:1 molar ratio) was added to the reaction mixture. ^g Compound (3a) (15%) was also obtained. ^h Compound (3b) (12%) was also obtained. ⁱ Silica gel, hexane–ether (2:1). ^j From hexane. ^k Compound (2g) (9%) was also obtained. ^l Compound (2h) (6%) was also obtained. ^m (*E*)- α -Iodostyryl thiocyanate (5%) was also obtained. ⁿ From ethanol. ^{*} From the mercury sulphinate [MeC₆H₄S(O)₂Hg].

of products (2) can be explained by considering a bridged geometry for the intermediate cation of type (4),⁹ which suffers a back attack by the nucleophile. Another possible mechanism, involving an intermediate of the mercurinium ion type (5),^{*} has been neglected because the acetoxymercuration of acetylenes takes place neither stereoselectively nor regioselectively.¹⁰ On the other hand, the literature additions of I–Nu reagents, such as ICl,⁴ *p*-MeC₆H₄SO₂I,⁵ MeCO₂I,⁷ and ArSO₃I,⁹ to alkynes, generally take place stereoselectively in a *trans* manner. Finally, a radical mechanism is also rejected because when the process was carried out in the dark no changes in the reaction time or in the regio- or stereo-chemistry were observed.



Experimental

General.—M.p.s are uncorrected and were measured on a Electrothermal melting-point apparatus. I.r. spectra were determined with a Perkin-Elmer 577 spectrometer. ¹H and ¹³C n.m.r. spectra were recorded on a Varian FT-80 spectrometer; CCl₄ was used as solvent and a D₂O capillary was employed as lock reference; SiMe₄ was used as internal standard for ¹H n.m.r. data, and ¹³C n.m.r. data are referenced to the solvent. M.s. (e.i.) were recorded with a Hewlett-Packard 5987A spectrometer. Microanalyses were performed with a Perkin-Elmer 240 Elemental Analyzer. T.l.c. analyses were carried out on Merck Kieselgel 60 F-254 plates (visualization by u.v.); column chromatography was performed at atmospheric pressure on Merck Kieselgel 60. Mercury(II) salts are mainly commercially available (Alfa, Aldrich, Fluka) or were prepared as was previously described.²

Preparation of Compounds (2) and (3). General Procedure.—To a mixture of alkyne (1) (5 mmol) and mercury(II) salt [(5

mmol for compounds (2) and 10 mmol for compounds (3)][†] was added iodine (1.3 g, 5 mmol) in small portions at 0 °C (bath temperature). The reaction mixture was stirred at 0 °C till no iodine colour was observed. The mercury(II) salt was filtered off, the filtrate was washed successively with 0.1M aqueous sodium thiosulphate and saturated aqueous potassium iodide, and dried with sodium sulphate, and the solvent was evaporated off (15 mmHg). The crude product was purified by column chromatography and the thermally stable compounds were then distilled or recrystallized (see Table) to afford the products (2) and (3). The following compounds were thus prepared.

(*E*)-3-Chloro-4-iodohex-3-ene (2a), ν_{\max} (neat) 1 630 cm⁻¹ (C=C); δ_{H} 1.05 and 1.10 (6 H, 2 t, *J* 7.5 Hz, 2 × Me), and 2.65 and 2.7 (4 H, 2 q, *J* 7.5 Hz, 2 × CH₂); δ_{C} 11.6 and 13.0 (2 × Me), 35.65 and 36.7 (2 × CH₂), 99.4 (Cl), and 131.7 (Cl); *m/z* 246 (*M*⁺ + 2, 28%), 244 (*M*⁺, 86), and 81 (100).

(*E*)-1-Ethyl-2-iodobut-1-enyl acetate (2b) (Found: C, 35.3; H, 4.7. C₈H₁₃IO₂ requires C, 35.84; H, 4.89%), ν_{\max} (neat) 1 760 (C=O) and 1 650 cm⁻¹ (C=C); δ_{H} (CDCl₃) 1.0 (6 H, t, *J* 7.5 Hz, 2 × Me) and 2.0–2.7 (7 H, m with a s at δ 2.18, Me and 2 × CH₂); δ_{C} (neat) 10.7 and 13.8 (2 × CH₃CH₂), 20.0 (CH₃CO), 29.5 and 30.8 (2 × CH₂), 95.6 (Cl), 148.35 (CO), and 166.7 (C=O); *m/z* 268 (*M*⁺, 2%) and 226 (100).

(*E*)-1-Ethyl-2-iodobut-1-enyl methanesulphonate (2c) (Found: C, 27.2; H, 4.0. C₇H₁₃IO₃S requires C, 27.64; H, 4.31%), ν_{\max} (neat) 1 650 (C=C), 1 360, and 1 150 cm⁻¹ (SO₂); δ_{H} 1.1 and 1.15 (6 H, 2 t, *J* 7.5 Hz, 2 × MeC), 2.63 and 2.65 (4 H, 2 q, *J* 7.5 Hz, 2 × CH₂), and 3.15 (3 H, s, MeS); δ_{C} 10.9 and 14.2 (2 × CH₃C), 29.9 and 31.4 (2 × CH₂), 38.8 (CH₃S), 100.85 (Cl), and 146.9 (CO); *m/z* 304 (*M*⁺, 12%) and 57 (100).

(*E*)-1-Ethyl-2-iodobut-1-enyl toluene-*p*-sulphonate (2d) (Found: C, 40.5; H, 4.1. C₁₃H₁₇IO₃S requires C, 41.06, H, 4.51%), ν_{\max} (neat) 1 650 (C=C), 1 370, and 1 160 cm⁻¹ (SO₂); δ_{H} 0.98 and 1.0 (6 H, 2 t, *J* 7.5 Hz, 2 × MeCH₂), 2.15–2.8 (7 H, m with s at δ 2.5, MeAr and 2 × CH₂), and 7.4 and 7.9 (4 H, 2 d, *J* 9 Hz, ArH); δ_{C} 10.9 and 14.3 (2 × CH₃CH₂), 21.6 (CH₃Ar), 29.7 and 31.2 (2 × CH₂), 101.4 (Cl), 127.6, 129.7, 134.0, and 144.8

^{*} We thank one referee for the suggestion of this alternative possibility.

[†] In the preparation of compounds (2g) and (2h) potassium thiocyanate (0.5 g, 5 mmol) was added to the reaction mixture.

(arylC), and 147.4 (CO); m/z 382 ($M^+ + 2$, 1%), 380 (M^+ , 16), and 57 (100).

(*E*)-3-Benzylthio-4-iodohex-3-ene (**2e**) (Found: C, 46.4; H, 3.2. $C_{13}H_{11}IS$ requires C, 47.00; H, 3.94%), v_{max} (neat) 3 060, 3 020, 1 600, 1 490, 760, and 700 cm^{-1} (Ar); δ_H 0.8 and 1.05 (6 H, 2 t, J 7.5 Hz, 2 \times Me), 2.4 and 2.6 (4 H, 2 q, J 7.5 Hz, 2 \times CH₂), 3.7 (2 H, s, CH₂S), and 7.15 (5 H, s, Ph); δ_C 12.2 and 14.1 (2 \times CH₃), 35.2, 36.7, and 38.0 (3 \times CH₂), 113.1 (CI), and 126.8, 128.2, 128.5, 135.9, and 137.4 (arylC and CS); m/z 241 ($M^+ - PhCH_2$, 5%) and 91 (100).

(*E*)-3-Iodo-4-(*p*-tolylsulphonyl)hex-3-ene (**2f**), v_{max} (Nujol) 1 650 (C=C), 1 380, and 1 160 cm^{-1} (SO₂); δ_H (CDCl₃) 1.05 and 1.1 (6 H, 2 t, J 7.5 Hz, 2 \times MeCH₂), 2.4 (3 H, s, MeAr), 2.7 and 3.25 (4 H, 2 q, J 7.5 Hz, 2 \times CH₂), and 7.45 and 7.9 (4 H, 2 d, J 9 Hz, ArH); δ_C 12.6 and 14.7 (2 \times CH₃CH₂), 21.5 (CH₃Ar), 34.05 and 37.4 (2 \times CH₂), 127.2, 129.8, 138.4, 144.2, and 145.3 (arylC and CS), and 128.85 (CI); m/z 364 (M^+ , 1%) and 157 (100).

(*E*)-1-Ethyl-2-iodobut-1-enylthiocyanate (**2g**) (Found: C, 31.1; H, 3.2. $C_7H_{10}INS$ requires C, 31.47; H, 3.77%), v_{max} (neat) 2 160 (SC≡N) and 1 600 cm^{-1} (C=C); δ_H 1.15 and 1.23 (6 H, 2 t, J 7.5 Hz, 2 \times Me), and 2.8 and 2.85 (4 H, 2 q, J 7.5 Hz, 2 \times CH₂); δ_C 11.7 and 13.7 (2 \times CH₃), 36.4 and 37.6 (2 \times CH₂), 107.9 (SCN), 112.6 (CI), and 125.65 (CSCN); m/z 267 (M^+ , 60%) and 79 (100).

(*E*)-1-Butyl-2-iodovinyl thiocyanate (**2h**) (Found: C, 30.9; H, 3.1. $C_7H_{10}INS$ requires C, 31.47; H, 3.77%), v_{max} (neat) 3 060 (HC=C) and 2 160 cm^{-1} (SC≡N); δ_H 1.0 (3 H, deformed t, Me), 1.5 (4 H, m, 2 \times CH₂), 2.6 (2 H, t, J 6 Hz, CH₂C=C), and 6.7 (1 H, s, CH); δ_C 13.8 (CH₃), 21.3, 30.6, and 39.6 (3 \times CH₂), 107.6 (SCN), 111.9 (CSCN), and 115.65 (CH); m/z 267 (M^+ , 4%) and 98 (100).

(*E*)- α -Chloro- β -iodo- β -(trimethylsilyl)styrene (**2i**) (Found: C, 38.8; H, 3.9. $C_{11}H_{14}ClISi$ requires C, 39.24; H, 4.19%), v_{max} (neat) 3 060, 3 020, 1 600, 1 520, 1 485, 750, and 695 cm^{-1} (Ar); δ_H 0.05 (9 H, s, 3 \times Me) and 7.4 (5 H, s, Ph); δ_C 1.1 (3 \times Me), 109.0 (CI), 128.0, 128.45, 129.0, 139.5 (arylC), and 145.8 (CCI); m/z 338 ($M^+ + 2$, 16%), 336 (M^+ , 46), and 93 (100).

(*E*)-2-Iodo-1-phenyl-2-(trimethylsilyl)vinyl acetate (**2j**) (Found: C, 43.0; H, 4.4. $C_{13}H_{17}IO_2Si$ requires C, 43.34; H, 4.76%), v_{max} (neat) 1 760 (C=O) and 1 630 cm^{-1} (C=C); δ_H 0.05 (9 H, s, 3 \times Me), 2.15 (3 H, s, MeCO), and 7.4 (5 H, s, Ph); δ_C 1.55 (3 \times CH₃), 20.8 (CH₃CO), 96.7 (CI), 127.7, 129.1, 129.6, and 132.1 (arylC), 135.7 (C-O), and 165.4 (C=O); m/z 318 ($M^+ - C_2H_2O$, 25%) and 175 (100).

(*E*)- α -Chloro- β -iodo- β -methylstyrene (**2k**), v_{max} (neat) 1 640 cm^{-1} (C=C); δ_H (CDCl₃) 2.75 (3 H, s, Me) and 7.4 (5 H, s, Ph); δ_C 31.3 (CH₃), 92.1 (CI), and 128.0, 128.4, 128.8, 128.9, and 141.2 (arylC and CCl); m/z 280 ($M^+ + 2$, 11%), 278 (M^+ , 34), and 115 (100).

(*E*)-2-Iodo-1-phenylprop-1-enyl acetate (**2l**), v_{max} (neat) 1 770 (C=O) and 1 600 cm^{-1} (C=C); δ_H 2.05 (3 H, s, MeCO), 2.5 (3 H, s, MeCl), and 7.2—7.6 (5 H, m, Ph); δ_C 20.8 (CH₃CO), 27.9 (CH₃Cl), 87.4 (CI), 128.4, 128.7, 130.1, and 137.7 (arylC), 147.2 (C-O), and 167.45 (C=O); m/z 302 (M^+ , 1%) and 260 (100).

(*E*)- β -Iodo- α -phenylstyryl acetate (**2m**), v_{max} (Nujol) 1 755 (C=O) and 1 610 cm^{-1} (C=C); δ_H (CDCl₃) 1.75 (3 H, s, Me) and 7.2—7.8 (10 H, m, Ph); δ_C (CDCl₃) 20.2 (CH₃), 88.9 (CI), 128.0, 128.1, 128.4, 129.2, 129.6, 137.6, and 141.3 (arylC), 148.0 (C-O), and 168.6 (C=O); m/z 322 ($M^+ - C_2H_2O$, 79%) and 165 (100).

(*E*)-3,4-Dithiocyanatohex-3-ene (**3a**), v_{max} (neat) 2 160 (SC≡N) and 1 600 cm^{-1} (C=C); δ_H 1.2 (6 H, t, J 7.5 Hz, 2 \times Me) and 2.7 (4 H, q, J 7.5 Hz, 2 \times CH₂); δ_C 12.3 (2 \times CH₃), 29.3 (2 \times CH₂), 106.8 (2 \times SCN), and 131.2 (C=C); m/z 198 (M^+ , 25%) and 73 (100).

(*E*)-1,2-Dithiocyanatohex-1-ene (**3b**), v_{max} (neat) 3 040 (HC=C), 2 160 (SC≡N), and 1 600 cm^{-1} (C=C); δ_H 1.0 (3 H, t, J 7.5 Hz, Me), 1.5 (4 H, m, 2 \times CH₂), 2.55 (2 H, t, J 7.5 Hz, CH₂C=C), and 6.55 (1 H, s, CH); δ_C 13.5 (CH₃), 21.7, 29.2, and 32.4 (3 \times CH₂), 107.15 and 107.65 (2 \times SCN), 114.5 (CH), and 136.1 (CSCN); m/z 198 (M^+ , 27%) and 98 (100).

(*E*)- α,β -Dithiocyanatostyrene (**3c**), v_{max} (CHCl₃) 2 160 (SC≡N) and 1 600 cm^{-1} (C=C); δ_H (CDCl₃) 6.85 (1 H, s, CHS) and 7.45 (5 H, m, Ph); δ_C (CDCl₃) 107.7 and 108.3 (2 \times SCN), 117.1 (CHS), 127.0 (CSCN), and 128.2, 129.2, 130.9, and 131.5 (arylC); m/z 218 (M^+ , 40%) and 102 (100).

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