Synthesis and Reactivity of β,γ-Dihalogenated Unsaturated Acids: Application to the Synthesis of 4-Substituted 5*H*-Furan-2-ones

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Abstract: β,γ-Dihalogenated unsaturated acids were prepared regio- and stereoselectively from allenic acid, and some aspects of their reactivities were studied.

Key words: α,β-unsaturated acids, halogenation, carboxylic acids, cross-coupling, organometallic reagents

Dihalogenated systems are very useful building blocks in organic chemistry. These compounds allow the development of plurifunctional systems, if the reactivity of both halogens is selectively controlled. Among these molecules, those bearing an ester or acidic function are particularly interesting,[1] but their synthesis constitutes a great challenge. Our efforts were focused on the synthesis of β,γ-dihalogenated unsaturated acids. We have already shown the usefulness of these moieties in the synthesis of pyrroles.[2] Only a few publications deal with the synthesis of this kind of molecules[3] while the greater part of the reports concerns with the synthesis of the ester derivatives.[4]

The β,γ-dihalogenated acids **2a–d** were obtained by adding symmetric (I_2, Br_2) and dissymmetric dihalogens (ICl, IBr) directly to buta-2,3-dienoic acid, which can be prepared via the method reported by Gaudemar[5] (Scheme 1).

Several variables in our experimental conditions were tested (temperature, solvent, concentration). Aprotic solvents (MeCN, CH_2Cl_2, Et_2O) were used to avoid HX addition on our substrate.[4a] Among them, Et_2O led to the best yields and selectivity. The reaction needs to be conducted in dilute solution (0.15 M), protected from light to avoid the formation of by-products.

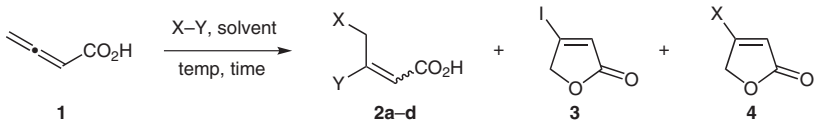
The control of the temperature in the reaction is very important. A high temperature causes the lowering of the regioselectivity and increases the formation of by-products. On the other hand, a low temperature (<0 °C) inhibits the reaction. The optimal conditions were determined for 6 mmol of buta-2,3-dienoic acid diluted in Et_2O (40 mL) with 1.5 equivalents of XY (0.15 M, Et_2O) at 4 °C for a time period of 24 to 45 hours (Table 1).

As expected with the use of aprotic solvents,[4a] the formation of by-product resulting from the addition of HX was not noticed. The use of a small amount of acetic acid[4a] increases the rate of the reactions even if the time of reactions were important (15 to 48 h).

In the case of dissymmetric dihalogens, the most electronegative halogen binds to the β-carbon while the other one is localized on the γ position. These results match with those already published on the synthesis of the ester homologue.[4a] The formation of γ-butenolides **3** and **4** up to 5% yield was also detected.

The *E*-stereoisomer is mainly obtained in all cases. The structure of our products was confirmed by NOE-DIFF and X-ray diffraction experiments. Data resulting from X-ray diffraction experiments performed on compounds **2a** (Figure 1), **2b** (Figure 2), **2c** (Figure 3), and **2d** (Figure 4) are given. Details of the crystal structure analysis are listed in Table 2.

These results obtained in term of selectivity can be explained by an internal control in transition state[4a] (Scheme 2). The halonium bridge is formed on the same side as the carboxylic function. This is favorized by the stabilization of this bridge by the carbonyl function. The subsequent attack by Y^- ion is then directed preferentially on the opposed side of the iodonium bridge on the most electrophilic β-carbon.



Scheme 1 Synthesis of 3,4-dihalobut-2-enoic acids

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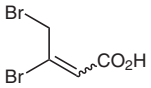
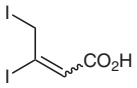
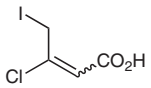
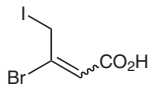
Table 1 Addition of X–Y to Buta-2,3-dienoic Acid

Entry	X–Y	Time (h)/Temp (°C)	Product		Ratio **2**/**3**/**4**	Ratio (*E*)-**2**/(*Z*)-**2**	Yield (%)
1	Br–Br	48/4	**2a**		100:0:0	65/35	80
2	I–I	15/4	**2b**		100:0:0	85/15	75
3	I–Cl	48/4	**2c**		94:2:4	83/17	70
4	I–Br	48/4	**2d**		90:5:5	60/40	62

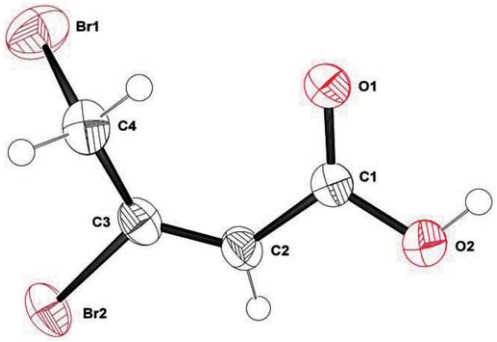


Figure 1 ORTEP drawing and labeling scheme for **2a** (ellipsoids are set at 50% probability). Bond lengths [Å]: C4–C3, 1.484(6); C4–Br1, 1.953(4); C3–C2, 1.320(5); C3–Br2, 1.907(4); C2–C1 1.471(5); C1–O1, 1.214(5); C1–O2, 1.318(5); angles [°]: C3–C1–Br1, 110.9(3); C2–C3–C4, 128.4(3); C2–C3–Br2, 117.1(3); C4–C3–Br2, 114.5(3); C3–C2–C1, 124.0(4); O1–C1–O2, 122.8(3); O1–C1–C2, 124.5(3); O2–C1–C2, 112.7(3).

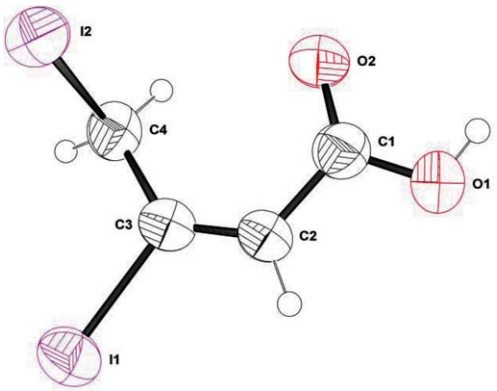


Figure 2 ORTEP drawing and labeling scheme for **2b** (ellipsoids are set at 50% probability). Bond lengths [Å]: C1–O2, 1.230(10); C1–O1, 1.300(10); C1–C2, 1.474(11); C2–C3, 1.304(10); 0.93; C3–C4, 1.508(10); C3–I1, 2.108(7); C4–I2, 2.155(8); angles [°]: O2–C1–O1, 123.0(8); O2–C1–C2, 124.4(8); O1–C1–C2, 112.6(7); C3–C2–C1, 124.8(7); C3–C2–H2, 117.6; C1–C2–H2, 117.6; C2–C3–C4, 128.2(7); C2–C3–I1, 117.2(5); C4–C3–I1, 114.6(6); C3–C4–I2, 110.4(5).

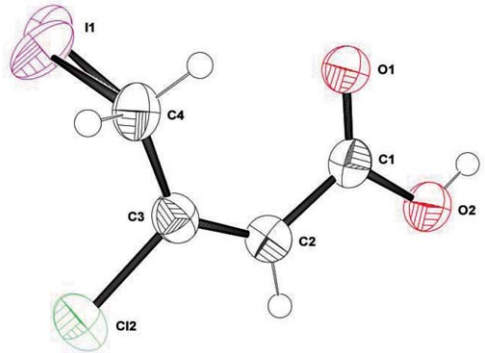


Figure 3 ORTEP drawing and labeling scheme for **2c** (ellipsoids are set at 50% probability). Bond lengths [Å]: C4–C3, 1.484(4); C4–I2, 1.992(6); C4–I1, 2.193(3); C3–C2, 1.329(3); C3–Cl2, 1.742(2); C2–C1, 1.465(3); C1–O1, 1.217(3); C1–O2, 1.320(3); angles [°]: C3–C4–I2, 109.5(2); C3–C4–I1, 111.12(16); C2–C3–C4, 127.9(2); C2–C3–Cl2, 117.94(19); C4–C3–Cl2, 114.17(18); C3–C2–C1, 125.0(2); O1–C1–O2, 122.8(2); O1–C1–C2, 125.5(2); O2–C1–C2, 111.7(2).

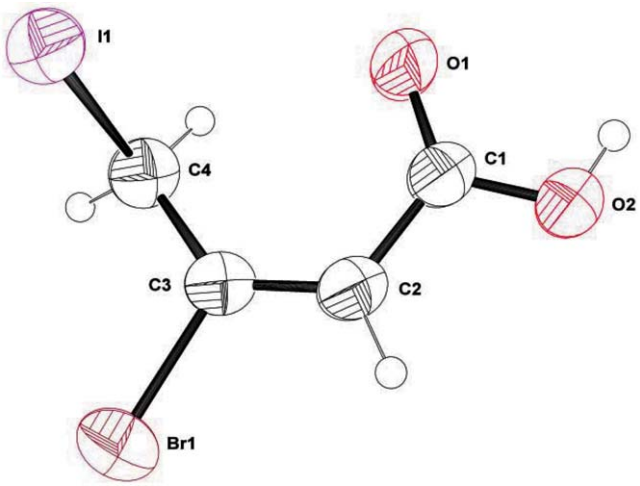
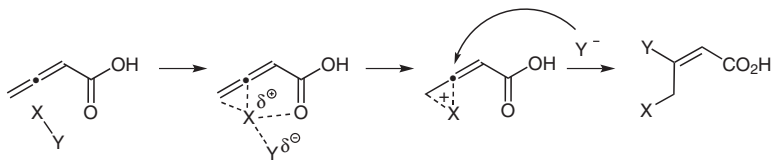


Figure 4 ORTEP drawing and labeling scheme for **2d** (ellipsoids are set at 50% probability). Bond lengths [Å]: I1–C4, 2.137(6); Br1–C3, 1.893(6); O2–C1, 1.306(7); O1–C1, 1.234(7); C1–C2, 1.458(9); C3–C2, 1.335(8); C3–C4, 1.468(8); angles [°]: O1–C1–O2, 122.3(6); O1–C1–C2, 124.5(6); O2–C1–C2, 113.2(5); C2–C3–C4, 128.1(5); C2–C3–Br1, 117.1(4); C4–C3–Br1, 114.8(4); C3–C2–C1, 124.8(5); C3–C4–I1, 110.8(4).

Table 2 Crystal and Structure Refinement Parameters of **2a**, **2b**, **2c**, and **2d**

Parameter	**2a**	**2b**	**2c**	**2d**
formula	$C_4H_4Br_2O_2$	$C_4H_4I_2O_2$	$C_4H_4ClIO_2$	$C_4H_4BrIO_2$
formula weight	243.89	675.74	246.42	581.76
temperature	293(2)	293(2)	293(2)	293(2)
crystal system	monoclinic	monoclinic	monoclinic	monoclinic
space group	P21/n	C2/c	P21/c	C2/c
a (Å)	5.1993(1)	24.586(5)	4.8806(1)	24.756(2)
b (Å)	10.4791(3)	7.410(5)	8.8071(2)	7.2482(7)
c (Å)	12.1849(4)	8.606(5)	16.0278(4)	8.2277(8)
α (°)	90	90.000(5)	90	90
β (°)	91.678(1)	101.504(5)	96.833(2)	101.389(3)
γ (°)	90	90.000(5)	90	90
V (Å^3)	663.60(3)	1536.4(14)	684.04(3)	1447.3(2)
Z	4	8	4	4
$\rho_{calc.}$ (g/cm^3)	2.441	2.921	2.393	2.67
μ (mm^{-1})	12.124	8.109	4.983	9.863
F(000)	456	1200	456	1056
c range (°)	3.35–28.67	2.88–28.16	2.64–28.66	2.93–28.63
index ranges	$0 \le h \le 6$, $0 \le k \le 14$, $16 \le l \le 16$	$-32 \le h \le 27$, $-9 \le k \le 7$, $-11 \le l \le 9$	$-6 \le h \le 6$, $-10 \le k \le 11$, $-21 \le l \le 20$	$-33 \le h \le 27$, $-8 \le k \le 9$, $11 \le l \le 9$
reflections collected	5880	7729	6682	5557
independent reflections	1646	1801	1669	1810
data/restraints/parameters	1646/0/74	1801/0/74	1669/0/83	1810/0/74
goodness-of-fit on F^2	1.154	1.018	1.042	1.08
R_{int}	–	0.0677	0.0385	0.0524
final *R* indices [$I > 2\sigma(I)$]	$R1 = 0.0372$	$R1 = 0.0491$	$R1 = 0.0267$	$R1 = 0.0449$
R indices (all data)	$wR2 = 0.0856$	$wR2 = 0.1209$	$wR2 = 0.0614$	$wR2 = 0.1072$

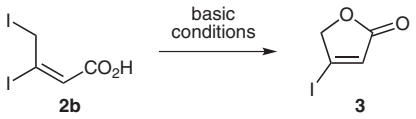


Scheme 2 Plausible mechanism for the formation of 3,4-dihalobut-2-enoic acids

Reactivity of (*E*)-3,4-Diiodobut-2-enoic Acid

The lactonization of (*E*)-3,4-diiodobut-2-enoic acid (**2b**) was investigated (Scheme 3). It yields 4-iodo-5*H*-furan-2-one (**3**),[6] which is one of the principal by-products reported earlier in the synthesis of 3,4-dihalobut-2-enoic acids **2a–d** (cf. Scheme 1). 5*H*-Furan-2-one moiety is prevalent in a variety of natural products,[7] which are medically important compounds.[8] Several of these compounds are drug active principles, for example Rofecoxib (Vioxx®)[9] or Benfurodil hemisuccinate (Eucilat®).[10]

As expected, a basic medium or a catalytic amount of palladium is sufficient to induce the cyclization, even if the use of an excess of *n*-BuNH$_2$ had a detrimental effect to



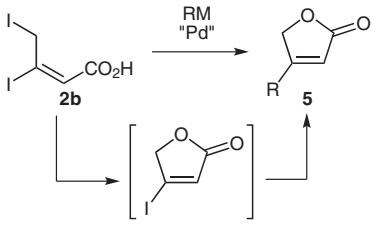
Scheme 3 Synthesis of 4-iodo-*5H*-furan-2-one

the reaction. Actually, a mixture of unknown by-products was obtained mainly. The best conditions are given in Table 3 (entries 5–7). These conditions are very interesting, since they are conditions of Stille and Suzuki cross-coupling, respectively. The most interesting conditions are described in entry 7. These palladium-free conditions led to the best yield of 4-iodo-5*H*-furan-2-one (**3**).

Considering the above results, the one-pot reaction of organotin and organoboronic acid derivatives with 3,4-dihalobut-2-enoic acids was investigated. Our plan was to achieve in one operation the cyclization and the cross-coupling on the vinylic iodide, in order to obtain 4-substituted 5*H*-furan-2-ones of type **5** (Scheme 4).[11] Thus, the reactions were carried out and a new possibility was found to acquire 4-substituted 5*H*-furan-2-ones in a one-pot reaction in average yields. The results given in Table 4 show that we were able to perform the cyclization and the subsequent Stille and Suzuki cross-couplings.

Table 3 Synthesis of 4-Iodo-5*H*-furan-2-one (**3**)

Entry	Conditions	Yield
1	DMF, 24 h, 40 °C	10
2	*n*-$BuNH_2$ (1 equiv), DMF, 5 h, 50 °C	66
3	*n*-$BuNH_2$ (2 equiv), DMF, 5 h, 50 °C	38
4	K_2CO_3 (1 equiv), DMF, 5 h, 50 °C	37
5	$PdCl_2(PPh_3)_2$ (5 mol%), DMF, 24 h, 60 °C	69
6	$Pd(PPh_3)_4$, toluene–H_2O–EtOH, Na_2CO_3 (1 M), 2 h, 40 °C	68
7	toluene–H_2O–EtOH, Na_2CO_3 (1 M), 2 h, 40 °C	75



Scheme 4 Synthesis of 4-substituted-*5H*-furan-2-ones

Table 4 Synthesis of 4-Substituted 5*H*-Furan-2-ones

Entry	Organometallic	Method[a]	Product	Yield (%)	Reference
1	$SnBu_3$	A	**5a**	54	–[6b]
2	Me_3Si, $SnBu_3$	A	**5b**	52	–[6b]
3	$SnBu_3$, $(CH_2)_4$	A	**5c**	52	–
4	$PhB(OH)_2$	B	**5d**	68	–[11n]
5	4-$MeC_6H_4B(OH)_2$	B	**5e**	60	–[11p]
6	4-$MeOC_6H_4B(OH)_2$	B	**5f**	59	–[11n]
7	*t*-Bu, $B(OH)_2$	B	**5g**	62	–

[a] Condtions A: **2b**, $PdCl_2(PPh_3)_2$ (0.03 equiv), $RSnBu_3$ (1.3 equiv), DMF, 80 °C. Condtions B: **2b**, $RB(OH)_2$ (1.3 equiv), $Pd(PPh_3)_4$ (0.03 equiv), Na_2CO_3, EtOH, toluene, 80 °C.

In summary, we have developed a new way to produce β,γ-dihalogenated unsaturated acids by direct halogenation of buta-2,3-dienoic acid. The dihalogenated acids obtained are useful building blocks to prepare the 5*H*-furan-2-one moiety. The use of Stille, Suzuki, or palladium-free Suzuki like conditions on the acids allowed us to synthesize 4-iodo-5*H*-furan-2-one and 4-substituted 5*H*-furan-2-ones in average yields.

All reactions were carried out under argon atmosphere in dried glassware. THF and Et_2O were dried and freshly distilled from sodium/benzophenone. Flash chromatography was carried out with Merck silica gel (silica gel, 230–400 mesh). ^1H NMR spectra were recorded on a Bruker AC 200 (200 MHz) NMR spectrometer, using $CDCl_3$ as solvent. Data, reported using the residual solvent proton resonance of $CDCl_3$ ($\delta_H = 7.25$ ppm) as internal reference, were as follows (in order): chemical shift (δ in ppm relative to Me_4Si), multiplicity (s, d, t, q, m, br for singlet, doublet, triplet, quartet, multiplet, broad) and coupling constants (*J* in Hz). ^{13}C NMR was recorded at 50 MHz on the same instruments, using the $CDCl_3$ solvent peak at ($\delta_C = 77.0$ ppm as reference. Mass spectra were obtained on a Hewlett Packard (engine 5989A) in direct introduction mode (70 eV). IR spectra were recorded on a Perkin-Elmer Spectrum One spectrophotometer. Melting points were uncorrected. Vinyltributyltin and isobutenyltributyltin were prepared from vinylmagnesium bromide and isobutenylmagnesium bromide and bis(tributyltin)oxide, respectively.[12] (*E*)-1-Trimethylsilyl-2-tributylstannylethylene[13] was prepared by hydrostannation of trimethylsilylacetylene; other vinyltin reagents were prepared by hydrostannation of the corresponding terminal alkynes under radical conditions (AIBN) and used as a thermodynamic mixture of *E*- and *Z*-isomers.

X-ray Crystallography[14]

Suitable single crystals of **2a**, **2b**, **2c**, and **2d** were mounted on a glass fiber. Data collections were carried out at r.t. on a Bruker-Nonius KappaCCD diffractometer equipped with graphite-monochromated Mo(Kα) radiation (λ = 0.71073 Å). Cell parameters were retrieved and refined using DENZO-SMN software[15] on all reflections. Data reductions were performed with the DENZO-SMN software. An empirical absorption correction based on the symmetry-equivalent reflections was applied to each data set using the SORTAV program.[16] The structure were solved either by SIR92[17] or SHELXS-97[18] and refined with the SHELXL-97 program.[19] The hydrogen atoms were placed in geometrically idealized positions and constrained to ride on their parent atoms.

3,4-Dihalobut-2-enoic Acids 2a–d; General Procedure

A dry round-bottomed double-necked flask (25 mL) equipped with a dropping funnel was charged with a solution of buta-2,3-dienoic acid (**1**; 0.5 g, 0.006 mol) in anhyd Et_2O (40 mL). A solution of X–Y (0.0072 mol) in a minimum of anhyd Et_2O was added dropwise to the solution of **1** via the dropping funnel at 0 °C (in the case of IBr addition, a 1 M commercial solution of dihalogen in CH_2Cl_2 was used). The mixture was stirred for 15 h or 48 h at 4 °C protected from the light, and was then hydrolyzed with aq 1 M solution of $Na_2S_2O_3$ until the mixture was decolored (for the addition reactions of Br_2, sat. aq $NaHSO_3$ was used to destroy the excess of Br_2). The organic phase was separated and the aqueous phase was extracted with Et_2O (3 × 15 mL). The combined organic layers were dried ($MgSO_4$), filtered, and concentrated at r.t. under reduced pressure. The compound obtained was purified by crystallization from CH_2Cl_2 (Table 1).

(*E*)-3,4-Dibromobut-2-enoic Acid (2a)

Yield: 80%; yellowish solid; mp 134–136 °C (CH_2Cl_2).

IR (KBr): 3065, 1702, 1617 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 4.85 (s, 2 H), 6.46 (s, 1 H), 8.70 (br s, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 31.4, 124.8, 144.5, 168.1.

MS (EI): *m*/*z* (%) = 244 [M^+].

***Z*-Isomer**

^1H NMR (200 MHz, $CDCl_3$): δ = 4.32 (s, 2 H), 6.76 (s, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 36.9, 122.0, 136.8, 168.4.

(*E*)-3,4-Diiodobut-2-enoic Acid (2b)

Yield: 75%; yellowish solid; mp 150–152 °C (CH_2Cl_2).

IR (KBr): 3071, 1683, 1592 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 5.08 (s, 2 H), 6.64 (s, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 10.9, 125.5, 131.1, 168.3.

MS (EI): *m*/*z* (%) = 254 (M – 84, 68), 226 (61), 211 (12), 210 (41), 180 (100), 152 (40), 128 (18), 127 (58), 99 (45), 84 (24), 83 (52), 55 (55), 53 (76), 45 (24), 43 (16), 39 (59), 38 (28), 37 (18).

***Z*-Isomer**

^1H NMR (200 MHz, $CDCl_3$): δ = 4.62 (s, 2 H), 6.73 (s, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 17.5, 117.8, 127.2, 169.2.

(*E*)-3-Chloro-4-iodobut-2-enoic Acid (2c)

Yield: 70%; yellowish solid; mp 92–93 °C (CH_2Cl_2).

IR (KBr): 3054, 1694, 1622 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 4.75 (s, 2 H), 6.17 (s, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 1.9, 119.1, 155.5, 169.7.

MS (EI, 70 eV): *m*/*z* (%) = 248 (2), 246 (5), 127 (14), 121 (10), 119 (32), 93 (4), 91 (14), 83 (19), 55 (24), 45 (26), 39 (100), 38 (38), 37 (21).

***Z*-Isomer**

^1H NMR (200 MHz, $CDCl_3$): δ = 4.18 (s, 2 H), 6.40 (s, 1 H).

(*E*)-3-Bromo-4-iodobut-2-enoic Acid (2d)

Yield: 62%; yellowish solid; mp 122–123 °C (CH_2Cl_2).

IR (KBr): 3084, 3047, 1683, 1605 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 4.93 (s, 2 H), 6.40 (s, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 4.8, 123.2, 147.3, 169.3.

MS (EI): *m*/*z* (%) = 292 (5), 290 (5), 211 (10), 165 (21), 163 (22), 137 (11), 135 (12), 127 (12), 84 (26), 55 (16), 45 (24), 40 (12), 39 (100), 38 (32), 37 (15).

***Z*-Isomer**

^1H NMR (200 MHz, $CDCl_3$): δ = 4.86 (s, 2 H), 6.47 (s, 1 H).

4-Iodo-5*H*-furan-2-one (3)

A mixture of 3,4-diiodobut-2-enoic acid (**2b**; 0.68 g, 2 mmol), EtOH (3 mL), H_2O (0.9 mL), toluene (4 mL) and aq Na_2CO_3 (2.5 mL, 1 M) was stirred at 40 °C for 2 h. The solvent was removed in vacuo. Sat. aq NH_4Cl (10 mL) was added and the aqueous layer was extracted with Et_2O (3 × 15 mL). The organic phase was washed with brine (10 mL), dried ($MgSO_4$), filtered, and concentrated in vacuo. Recrystallization from petroleum ether (bp 40–60 °C)–Et_2O gave **3**[6b] (315 mg, 75%) as white needles; mp 109–110 °C.

IR (KBr): 1774, 1729, 1585 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 4.86 (d, *J* = 1.9 Hz, 2 H), 6.57 (t, *J* = 1.9 Hz, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 77.8, 117.3, 128.4, 170.2.

MS (EI, 70 eV): *m*/*z* (%) = 210 (59), 152 (13), 127 (17), 83 (100), 55 (32), 39 (69).

4-Substituted 5*H*-Furan-2-ones 5; General Procedure

Stille Procedure: A dry Schlenk tube (25 mL) equipped with a teflon-coated magnetic stirrer was charged with (*E*)-3,4-diiodobut-2-enoic acid (**2b**; 0.68 g, 2 mmol), $PdCl_2(PPh_3)_2$ (0.06 mmol, 0.03 equiv), and freshly distilled DMF (3 mL). The mixture was stirred at r.t. for 15 min, and the respective organotin reagent (2.6 mmol, 1.3 equiv) was added. The mixture was stirred again at 80 °C for 24 h, followed by the addition of another portion of $PdCl_2(PPh_3)_2$ (0.03 equiv). After cooling, the mixture was filtered over a Celite pad. The solvent was evaporated and the residue was treated with EtOAc (3 mL) and aq 1 M KF (3 mL). The mixture was vigorously stirred for 2 h, then filtered over a Celite pad, and extracted with Et_2O (3 × 10 mL). The organic portions were combined, washed with brine (10 mL), and dried ($MgSO_4$). After evaporation of the solvent, the crude product was purified by flash chromatography on silica gel to give the desired 5*H*-furan-2-ones (Table 4).

Suzuki Procedure: A dry Schlenk tube (25 mL) equipped with a teflon-coated magnetic stirrer and containing EtOH (3.2 mL), H_2O (0.9 mL), and toluene (4.0 mL) was charged with (*E*)-3,4-diiodobut-2-enoic acid (**2b**; 0.68 g, 2 mmol) and the respective boronic acid (2.6 mmol, 1.3 equiv). Aq 1 M Na_2CO_3 (2.5 mL) and $Pd(PPh_3)_4$ (0.06 mmol, 0.03 equiv) were added, and then the mixture was stirred at 80 °C for 2 h. The reaction was quenched with aq NH_4Cl (10 mL). The residue was diluted with Et_2O (15 mL) and filtered through a Celite pad. The organic solvents were evaporated from the filtrate and the aqueous medium obtained was extracted with Et_2O (3 × 20 mL). The organic portions were combined and dried ($MgSO_4$). After evaporation of the solvent, the crude product was purified by flash chromatography on silica gel to give the desired 5*H*-furan-2-ones (Table 4).

4-Vinyl-5*H*-furan-2-one (5a)[6b]

Yield: 54%; orange oil.

IR (NaCl): 3102, 1781, 1744, 1643, 1583 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 4.98 (d, *J* = 1.7 Hz, 2 H), 5.60 (d, *J* = 10.8 Hz, 1 H), 5.61 (d, *J* = 17.8 Hz, 1 H), 5.96 (br s, 1 H), 6.69 (dd, *J* = 17.8, 10.8 Hz, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 70.8, 116.7, 123.7, 128.3, 162.5, 174.2.

MS (EI): *m*/*z* (%) = 110 (40), 81 (100), 53 (84), 52 (57), 51 (23), 50 (17), 39 (16).

4-[(2-Trimethylsilyl)vinyl]-5*H*-furan-2-one (5b)[6b]

Yield: 52%; orange oil.

IR (NaCl): 3102, 1779, 1745, 1627, 1566 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 0.14 (s, 9 H), 4.97 (d, *J* = 1.6 Hz, 2 H), 5.92 (br s, 1 H), 6.36 (d, *J* = 19.3 Hz, 1 H), 6.84 (d, *J* = 19.3 Hz, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = –2.9 (3 C), 69.6, 114.5, 132.8, 141.6, 161.8, 175.5.

MS (EI, 70 eV): *m*/*z* (%) = 182 (19), 167 (20), 139 (13), 123 (22), 111 (18), 83 (10), 73 (100), 59 (25), 45 (16), 43 (15).

Hept-4-ynyl-5*H*-furan-2-one (5c)

Yield: 48%; orange oil.

IR (NaCl): 2226, 1780, 1750, 1610 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 0.92 (t, *J* = 6.9 Hz, 3 H), 1.26–1.65 (m, 6 H), 2.46 (t, *J* = 6.9 Hz, 2 H), 4.78 (d, *J* = 1.8 Hz, 2 H), 6.10 (s, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 14.3, 20.3, 22.5, 28.1, 31.5, 71.9, 73.7, 108.7, 121.8, 148.7, 174.1.

MS (EI, 70 eV): *m*/*z* (%) = 178 (2), 163 (10), 149 (22), 136 (20), 122 (11), 121 (15), 119 (21), 107 (12), 106 (15), 105 (51), 93 (25), 92 (42), 91 (89), 81 (25), 79 (56), 78 (23), 77 (41), 68 (15), 67 (16), 66 (15), 65 (28), 64 (20), 63 (67), 62 (14), 57 (16), 55 (88), 53 (13), 51 (40), 50 (17), 42 (24), 41 (100), 39 (51).

4-Phenyl-5*H*-furan-2-one (5d)[11n]

Yield: 68%; white solid; mp 90–91 °C.

IR (KBr): 3110, 3057, 1786, 1749, 1625, 1578 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 5.23 (d, *J* = 1.7 Hz, 2 H), 6.38 (t, *J* = 1.7 Hz, 1 H), 7.48–7.53 (m, 5 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 71.5, 113.4, 126.9 (2 C), 129.7 (2 C), 130.0, 132.2, 164.4, 174.4.

MS (EI, 70 eV): *m*/*z* (%) = 160 (52), 132 (10), 131 (100), 103 (60), 102 (43), 77 (29), 76 (14), 63 (10), 51 (36), 50 (15).

4-*p*-Tolyl-5*H*-furan-2-one (5e)[11p]

Yield: 60%; white solid; mp 117–118 °C.

IR (KBr): 3055, 1787, 1755, 1744, 1623 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 2.42 (s, 3 H), 5.20 (d, *J* = 1.7 Hz, 2 H), 6.32 (t, *J* = 1.7 Hz, 1 H), 7.28 (d, *J* = 8.1 Hz, 2 H), 7.41 (d, *J* = 8.1 Hz, 2 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 21.9, 71.4, 112.2, 126.8 (2 C), 127.3, 130.4 (2 C), 142.9, 164.5, 174.6.

MS (EI, 70 eV): *m*/*z* (%) = 174 (77), 146 (11), 145 (100), 117 (37), 116 (31), 115 (56), 91 (12), 65 (12), 51 (10), 39 (14).

4-(4-Methoxyphenyl)-5*H*-furan-2-one (5f)[11n]

Yield: 59%; white solid; mp 107–108 °C.

IR (KBr): 3057, 1786, 1751, 1625 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 3.87 (s, 3 H), 5.20 (d, *J* = 1.7 Hz, 2 H), 6.24 (d, *J* = 1.7 Hz, 1 H), 6.97 (d, *J* = 8.9 Hz, 2 H), 7.46 (d, *J* = 8.9 Hz, 2 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 55.9, 71.4, 110.9, 115.1 (2 C), 122.6, 128.6 (2 C), 162.8, 164.2, 174.9.

MS (EI, 70 eV): *m*/*z* = 190 (100), 161 (93), 133 (44), 132 (56), 118 (14), 117 (31), 103 (12), 90 (15), 89 (52), 77 (23), 63 (38), 51 (22), 39 (19).

(4*E*)-3,3-Dimethylbut-1-enyl-5*H*-furan-2-one (5g)

Yield: 62%; yellow oil.

IR (NaCl): 1778, 1747, 1645, 1594 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 1.11 (s, 9 H), 4.97 (d, *J* = 1.5 Hz, 2 H), 5.88 (d, *J* = 1.5 Hz, 1 H), 6.11 (d, *J* = 16.4 Hz, 1 H), 6.34 (d, *J* = 16.4 Hz, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 29.2 (3 C), 34.5, 71.0, 114.5, 117.1, 152.0, 163.4, 174.6.

MS (EI, 70 eV): *m*/*z* (%) = 166 (54), 151 (23), 123 (37), 121 (24), 109 (47), 107 (100), 105 (17), 96 (37), 95 (33), 93 (53), 91 (74), 81 (12), 79 (58), 77 (56), 70 (31), 67 (40), 65 (27), 55 (36), 53 (29), 51 (32), 43 (32), 41 (82), 39 (65).

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