On the 6-Exo Atom Transfer Radical Cyclization Reactions of 3-Butenyl 2-Iodoalkanoates

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Abstract: Bis(tributyltin) initiated atom transfer cyclization reactions of 3-butenyl iodoalkanoates in the presence of $\text{BF}_3\cdot\text{OEt}_2$ as the catalyst afforded the 6-exo cyclization products as a mixture of 3,4-cis- and trans-substituted tetrahydro-2H-pyran-2-ones in 53-71% yield with the major isomers being the cis ones. Ab initio calculations at B3LYP/6-31G* level on the transition states of the radical cyclization and on the cyclized products revealed that the reactions are kinetically controlled and the transition states for the 6-exo radical cyclization are in boat conformations. Moreover, the cis-oriented transition states are of lower energy than the corresponding trans-oriented ones, which are in excellent agreement with the experimental results.

Supporting Information

Compounds **5a-d** were prepared by esterification of (substituted) 3-buten-1-ol with 2-chloropropionic acid in CH_2Cl_2 at 0°C in the presence of DCC and 10% DMAP as catalyst followed by iodine exchange with NaI in acetone. Compound **5e** was synthesized by α -iodination of butyric acid followed by reaction with 3-buten-1-ol in CH_2Cl_2 at 0°C in the presence of DCC and 10% DMAP as catalyst. Compound **5f-h** were prepared by esterification of 3-buten-1-ol with corresponding carboxylic acid in CH_2Cl_2 at 0°C in the presence of DCC and 10% DMAP as catalyst followed by α -iodination with LDA and I_2 .

3-Butenyl 2-iodopropionate (5a). Pale yellow liquid. B.p. $76-77^\circ\text{C}/1\text{mmHg}$. ^1H NMR (300 MHz, CDCl_3) 1.954 (3H, d, $J = 7.0$ Hz, CH_3), 2.382-2.457 (2H, m, CH_2), 4.133-4.271 (2H, m, CH_2O), 4.478 (1H, q, $J = 7.0$ Hz, CHI), 5.083-5.176 (2H, m, $\text{CH}_2=$), 5.736-5.872 (1H, m, $\text{CH}=$). ^{13}C NMR (CDCl_3) 171.86, 133.58, 117.57, 64.75, 32.73, 23.37, 12.97. EIMS: m/z (relative intensity) 254 (M^+ , 6), 183 (37), 155 (30), 127 (25), 83 (25), 69 (21), 55 (91), 54(100), 41(35). Anal. calcd for $\text{C}_7\text{H}_{11}\text{IO}_2$: C, 33.09; H, 4.36. Found: C, 32.81; H, 4.36.

4-Penten-2-yl 2-iodopropionate (5b). Pale yellow liquid. B.p. $56-58^\circ\text{C}/1\text{mmHg}$. ^1H NMR (300 MHz, CDCl_3) 1.240 (3H, d, $J = 6.3$ Hz, CH_3), 1.946 (3H, d, $J = 7.0$ Hz, CH_3), 2.280-2.407 (2H, m, CH_2), 4.415-4.510 (1H, m, CHO), 4.997 (1H, q, $J = 6.3$ Hz, CHI), 5.072-5.147 (2H, m, $\text{CH}_2=$), 5.718-5.843 (1H, m, $\text{CH}=$). ^{13}C NMR (CDCl_3) 171.37/171.34, 133.35/133.21, 118.14/117.99, 71.61, 40.01/39.75, 23.32/23.30, 19.08/18.60, 13.89/13.73. EIMS: m/z (relative intensity) 268 (M^+ , 2), 254 (5), 227 (12), 183 (30), 155 (16), 97 (61), 69 (56), 55 (100), 41 (51). Anal. calcd for $\text{C}_8\text{H}_{13}\text{IO}_2$: C, 35.84; H, 4.89. Found: C, 36.20; H, 5.02.

2-Methyl-3-butenyl 2-iodopropionate (5c). Pale yellow liquid. B.p. $83-86^\circ\text{C}/1\text{mmHg}$. ^1H NMR (300 MHz, CDCl_3) 1.077 (3H, d, $J = 6.6$ Hz, CH_3), 1.959 (3H, d, $J = 7.0$ Hz, CH_3), 2.520-2.625 (1H, m, CH), 3.935-4.138 (2H, m, CH_2O), 4.483 (1H, q, $J = 7.0$ Hz, CHI), 5.049-5.135 (2H, m, $\text{CH}_2=$), 5.695-5.793 (1H, m, $\text{CH}=$). ^{13}C NMR (CDCl_3) 171.88, 139.65/139.59, 115.37, 69.51, 36.99/36.88, 23.47, 16.40, 13.02. EIMS: m/z (relative intensity) 268 (M^+ , 4), 253 (2), 198 (4), 141 (13), 113 (10), 97 (23), 83 (15), 69 (21), 55 (100), 41 (35). Anal. calcd for $\text{C}_8\text{H}_{13}\text{IO}_2$: C, 35.84; H, 4.89. Found: C, 35.83; H, 4.87.

threo-3-Methyl-4-penten-2-yl 2-iodopropionate (5d). Pale yellow liquid. B.p. $45-48^\circ\text{C}/0.15\text{mmHg}$. ^1H NMR (300 MHz, CDCl_3) 1.034 (1.5H, d, $J = 7.1$ Hz, CH_3)/1.063 (1.5H, d, $J = 6.9$ Hz, CH_3), 1.167 (3H, d, $J = 6.5$ Hz, CH_3), 1.940 (3H, d, $J = 7.0$ Hz, CH_3), 2.337-2.448 (1H, m, CH), 4.408-4.497 (1H, m, CHI), 4.805-4.942 (1H, m, CHO), 5.031-5.118 (2H, m, $\text{CH}_2=$), 5.667-5.816 (1H, m, $\text{CH}=$). ^{13}C NMR (CDCl_3) 171.37, 139.39/139.12, 115.97/115.82, 75.25/75.01, 42.70/42.55, 23.45/23.43, 16.68/16.17, 15.72, 14.07/13.74. EIMS: m/z (relative intensity) 282 (M^+ , 0.7), 227 (24), 183 (100), 155 (51), 111 (14), 83 (79), 55 (63), 41 (17). HRMS calcd for $\text{C}_9\text{H}_{15}\text{IO}_2$: 282.0117. Found: 282.0155. Anal. calcd for $\text{C}_9\text{H}_{15}\text{IO}_2$: C, 38.32; H, 5.36. Found: C, 39.06; H, 5.33.

3-Butenyl 2-iodobutyrate (5e). Pale yellow liquid. B.p. $52-55^\circ\text{C}/0.4\text{mmHg}$. ^1H NMR (300 MHz, CDCl_3) 0.964 (3H, t, $J = 7.3$ Hz, CH_3), 1.939-2.041 (2H, m, CH_2), 2.381-2.456 (2H, m, CH_2), 4.168-4.271 (3H, m, CH_2O and CHI), 5.075-5.174 (2H, m, $\text{CH}_2=$), 5.732-5.868 (1H, m, $\text{CH}=$). ^{13}C NMR (CDCl_3) 171.38, 133.66, 117.63, 64.74, 32.83, 29.64, 23.13, 14.11. EIMS: m/z (relative intensity) 269 ($\text{M}^+ + 1$, 23), 197 (30), 169 (20), 69 (7), 55 (100), 54 (76), 41 (26). Anal. calcd for $\text{C}_8\text{H}_{13}\text{IO}_2$: C, 35.84; H, 4.89. Found: C, 35.72; H, 4.78.

3-Butenyl 2-iodo-3-methylbutyrate (5f). Pale yellow liquid. B.p. $50-53^\circ\text{C}/0.05\text{mmHg}$. ^1H NMR (300 MHz, CDCl_3) 1.005 (3H, d, $J = 6.6$ Hz, CH_3), 1.112 (3H, d, $J = 6.6$ Hz, CH_3), 1.924-2.040 (1H, m, CH), 2.374-2.448 (2H, m, CH_2), 4.103 (1H, d, $J = 8.6$ Hz, CHI), 4.195 (2H, t, $J = 6.6$ Hz, CH_2O), 5.062-5.166 (2H, m, $\text{CH}_2=$), 5.724-5.860 (1H, m, $\text{CH}=$). ^{13}C NMR (CDCl_3) 170.88, 133.61, 117.52, 64.61, 32.73, 32.42, 22.67, 20.14. EIMS: m/z (relative intensity) 283 ($\text{M}^+ + 1$, 7), 211 (11), 183 (12), 101 (7), 95 (5), 69 (15), 55 (100), 41 (17). Anal. calcd for $\text{C}_9\text{H}_{15}\text{IO}_2$: C, 38.32; H, 5.36. Found: C, 38.36; H, 5.21.

3-Butenyl 4,4-dimethyl-2-iodopentanoate (5g). Pale yellow oil. ^1H NMR (300 MHz, CDCl_3) 0.738 (9H, s, CH_3), 1.945 (1H, dd, $J = 14.2, 2.7$ Hz, CH_2), 2.160 (2H, q, $J = 6.7$ Hz, CH_2), 2.650 (1H, dd, $J = 14.2, 11.4$ Hz, CH_2), 3.949-4.077 (2H, m, CH_2O), 4.498 (1H, dd, $J = 11.4, 2.7$ Hz, CHI), 4.979-2.042

(2H, m, CH₂=), 5.570-5.706 (1H, m, CH=). EIMS: *m/z* (relative intensity) 311(M⁺+1, 29), 257 (10), 239 (9), 183 (6), 129 (21), 127 (30), 55 (100), 41 (49). HRMS calcd for C₉H₁₅IO₂: 310.0430. Found: 310.0401.

3-Butenyl 2-iodo-3,3-dimethylbutyrate (5h). Pale yellow liquid. B.p. 58-60°C/0.1mmHg. ¹H NMR (300 MHz, CDCl₃) 1.157 (9H, s, CH₃), 2.369-2.444 (2H, m, CH₂), 4.173 (2H, t, *J* = 6.6 Hz, CH₂O), 4.241 (1H, s, CHI), 5.069-5.166 (2H, m, CH₂=), 5.722-5.858 (1H, m, CH=). ¹³C NMR (CDCl₃) 170.51, 133.69, 117.52, 64.44, 38.54, 33.96, 32.77, 27.60. EIMS: *m/z* (relative intensity) 297 (M⁺+1, 7), 225 (14), 197 (14), 169 (11), 127 (10), 86 (27), 69 (16), 55 (100), 41 (28). Anal. calcd for C₁₀H₁₇IO₂: C, 40.56; H, 5.79. Found: C, 40.18; H, 5.73.

Scheme S1. Crystal structures of the dimmers formed in the reaction of **1**.

Chart S1. Computational (B3LYP/6-31G*) results on the transition states.

%chk=C-1

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for C-1 HF = -384.408319

0 2

1	-0.772152	-1.241243	-1.794513
6	-0.559129	-1.109843	-0.740275
8	1.150570	-0.624088	0.891516
6	-0.495716	1.190987	1.045194
6	0.110062	-0.057046	1.694529
6	-1.341354	0.938310	-0.188202
6	0.856903	-0.995933	-0.396632
1	-0.662458	-0.804046	1.923210
1	-1.118261	1.694577	1.798851
1	0.601821	0.207235	2.634083
1	0.324056	1.876254	0.798831
8	1.770469	-1.193153	-1.172031
1	-1.230651	-1.613334	-0.051346
1	-2.299764	0.452768	-0.008859
6	-1.222561	1.700456	-1.321044
1	-0.354355	2.332239	-1.489502
1	-1.945780	1.631889	-2.128057

%chk=T-1

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for T-1 HF = -384.407236

0 2

1	-1.249080	-1.391699	1.804175
6	1.136552	-0.217044	-0.769826
8	0.139849	1.466231	0.646148
6	-1.135952	-0.614568	1.037548
6	-0.110306	0.400039	1.565614
6	-0.809308	-1.263203	-0.300242
6	0.668455	1.155063	-0.580599
1	0.826034	-0.100693	1.841851
1	-2.104212	-0.106295	0.952136
1	-0.498902	0.889381	2.462326
1	-1.203385	-0.758591	-1.179716
8	0.681122	2.007497	-1.446502
1	1.724441	-0.704397	-0.000446
1	1.368260	-0.491397	-1.792444
6	-0.529367	-2.599623	-0.412807
1	-0.298164	-3.207179	0.459034
1	-0.453203	-3.082934	-1.382206

%chk=C-5a

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for C-5a HF=-423.7288485

0 2

6	-0.713382	-1.067488	-2.036300
6	-0.434218	-0.896382	-0.574508
8	1.209819	-0.552183	1.170127
6	-0.469148	1.211995	1.425431
6	0.134473	-0.077660	1.986599
6	-1.219817	1.063660	0.114129
6	0.969933	-0.794010	-0.158081
1	-0.629501	-0.855425	2.122718
1	-1.153144	1.624699	2.180887
1	0.590518	0.109593	2.962093
1	0.344257	1.937121	1.302699
8	1.915303	-0.899238	-0.914427
1	-1.093324	-1.429736	0.107176
1	-2.193458	0.579336	0.183615
6	-1.042190	1.962452	-0.912781
1	-0.172499	2.613489	-0.948946
1	-1.709635	1.986430	-1.768618
1	-0.121867	-0.367573	-2.632256
1	-1.776085	-0.921265	-2.258614
1	-0.440147	-2.080707	-2.363293

%chk=T-5a

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for T-5a HF = -423.7279114

0 2

1	-1.10646	-1.36151	2.2253
6	0.86536	-0.14222	-0.63286
8	0.08374	1.52844	0.9419
6	-1.11209	-0.56163	1.47407
6	-0.03456	0.45442	1.87784
6	-0.96927	-1.16582	0.08268
6	0.42225	1.22972	-0.35191
1	0.93402	-0.04018	2.02374
1	-2.08913	-0.06772	1.54161
1	-0.30429	0.93386	2.82228
1	-1.50013	-0.64525	-0.7123
8	0.30113	2.09112	-1.20186
1	1.51744	-0.60994	0.09915
6	1.10347	-0.5116	-2.06503
6	-0.74683	-2.51167	-0.09354
1	-0.40154	-3.14062	0.72363
1	-0.82801	-2.97773	-1.07067
1	2.0427	-0.06877	-2.42604
1	0.30712	-0.12879	-2.71036
1	1.17937	-1.59716	-2.18403

%chk=C-5a*

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for C-5a* HF = -423.721566

0 2

1	-1.799180	-1.117331	1.749756
6	0.785766	-0.134347	-0.882869
8	0.054578	1.527370	0.750864
6	-1.489707	-0.390744	0.987609
6	-0.371223	0.454792	1.602693
6	-1.130215	-1.125240	-0.298429
6	0.425760	1.256127	-0.536926
1	0.475143	-0.178885	1.886278
1	-2.351113	0.262259	0.803107
1	-0.731547	0.954300	2.506015
1	-1.529591	-0.692011	-1.212827
8	0.430736	2.162388	-1.345372
6	1.970443	-0.818468	-0.247214
1	0.700405	-0.303084	-1.953730
6	-0.870916	-2.474909	-0.307739
1	-0.667946	-3.022905	0.609526
1	-0.780564	-3.028332	-1.237963
1	2.882591	-0.564731	-0.806194
1	1.860515	-1.908784	-0.281636
1	2.139324	-0.521819	0.790976

%chk=T-5a*

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for T-5a* HF = -423.719808

0 2

1	-1.065526	-2.795810	-0.815905
6	-0.331520	-0.777377	-0.857482
8	1.256635	-0.513987	0.984128
6	-0.249700	1.437676	1.067232
6	0.257386	0.170737	1.753675
6	-1.140635	1.199764	-0.134572
6	1.055267	-0.740248	-0.350868
1	-0.574875	-0.499480	2.002047
1	-0.816011	2.013973	1.813842
1	0.766851	0.423612	2.687153
1	0.613413	2.051961	0.782570
8	2.023810	-0.911099	-1.062706
6	-1.301291	-1.821664	-0.361435
1	-2.072240	0.675854	0.079011
6	-1.117592	2.031023	-1.226214
1	-0.283652	2.704225	-1.407742

1	-1.882163	1.977628	-1.995594
1	-2.330394	-1.576886	-0.650286
1	-1.272696	-1.961138	0.722460
1	-0.357746	-0.612720	-1.930945

%chk=C-5d

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for C-5d HF=-502.3600995

0 2

6	-0.857774	-0.548052	-2.812027
6	-0.826400	-0.557265	-1.315205
1	0.154520	-0.538782	-3.224106
1	-1.411877	0.316532	-3.194094
1	-1.352457	-1.453747	-3.191199
6	0.125931	-1.452834	-0.654912
1	-1.775902	-0.399974	-0.809256
8	0.211854	-1.373041	0.708666
8	0.844600	-2.238096	-1.243160
6	-0.351431	-0.245486	1.409384
6	0.297062	1.062916	0.901223
1	-1.437566	-0.209072	1.240771
6	-0.095852	-0.539761	2.883982
6	-0.014424	1.382042	-0.557616
6	-0.099388	2.277350	1.765037
1	1.381861	0.912075	0.988130
1	-1.012485	1.783370	-0.737355
6	0.977307	1.760237	-1.430787
1	2.023063	1.546295	-1.225352
1	0.746543	2.194445	-2.398779
1	0.975878	-0.499230	3.107481
1	-0.454460	-1.545520	3.120988
1	-0.618722	0.172252	3.528520
1	0.342601	3.190666	1.354785
1	0.245609	2.170592	2.797676
1	-1.188407	2.414318	1.783264

%chk=T-5d

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for T-5d HF=-502.3576345

0 2

6	-0.291892	-0.535853	-2.621380
6	-0.438824	-0.861201	-1.127833
6	0.973374	-1.018777	-0.487779
6	-1.361776	0.106372	-0.384489
1	-0.925247	-1.844809	-1.041573

8	0.957593	-0.890665	0.944744
1	1.634051	-0.244725	-0.902324
6	1.593387	-2.386595	-0.753443
1	-1.686957	-0.254662	0.589848
6	-2.211926	0.987595	-1.011001
6	0.557958	0.285022	1.521205
1	-2.081961	1.293992	-2.043809
1	-2.999326	1.484707	-0.453132
6	0.158734	1.371582	0.622999
8	0.478056	0.340966	2.734401
1	0.742029	1.526271	-0.279904
6	-0.454329	2.592991	1.234890
1	0.321652	3.229176	1.684493
1	-1.149256	2.326600	2.036395
1	-0.979360	3.188539	0.481126
1	2.596574	-2.436417	-0.320260
1	1.670394	-2.585160	-1.826880
1	0.983499	-3.172305	-0.295116
1	0.379951	-1.244697	-3.115300
1	0.118066	0.470487	-2.772585
1	-1.257543	-0.586210	-3.133150

%chk=C-5e

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for C-5e HF= - 463.0428921

0 2

1	3.086647	0.980409	0.590505
6	-0.560586	-0.073217	0.552512
8	1.090984	-1.514517	-0.476084
6	2.218689	0.597572	0.034840
6	2.056316	-0.886013	0.373356
6	1.014800	1.470669	0.343059
6	-0.178394	-0.998843	-0.521504
1	1.803516	-1.032695	1.432212
1	2.464077	0.674001	-1.031128
1	2.987445	-1.424526	0.179287
1	0.836588	2.346074	-1.614768
8	-0.905196	-1.319609	-1.442394
6	-3.047058	-0.391090	0.894648
6	-1.916474	0.570231	0.479763
1	-0.163285	3.160042	-0.285736
6	0.561125	2.401319	-0.564788
1	0.853051	1.690296	1.397995
1	-2.907604	-0.754843	1.919942
1	-0.216735	-0.340998	1.550530
1	-2.093766	0.914606	-0.544231
1	-3.075877	-1.253179	0.222775
1	-4.017898	0.115914	0.848053

1 -1.932977 1.454140 1.131075

%chk=T-5e

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for T-5e HF=-463.0394869

0 2

1	-0.918947	-1.011648	2.773400
6	0.762937	-0.273728	-0.408028
8	0.507559	1.577996	1.135226
6	-0.917691	-0.251982	1.981360
6	0.354814	0.588550	2.154994
6	-1.095123	-0.923746	0.626282
6	0.640613	1.171065	-0.167038
1	1.243365	-0.052937	2.205250
1	-1.782983	0.397564	2.162128
1	0.305721	1.154597	3.088766
1	-1.652164	-0.347061	-0.108344
8	0.623551	2.018796	-1.039991
1	1.407731	-0.811552	0.281677
6	0.796757	-0.782380	-1.827689
6	-1.129764	-2.293213	0.501704
1	-0.767078	-2.944426	1.293568
1	-1.439771	-2.771259	-0.422566
1	-0.546826	0.659880	-2.750503
6	-0.405396	-0.422297	-2.712996
1	0.923414	-1.871442	-1.798811
1	-1.328874	-0.883558	-2.344283
1	-0.242887	-0.785178	-3.733804
1	1.707530	-0.380930	-2.299888

%chk=C-5h

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for C-5h HF=-541.665224

0 2

1	-3.193201	1.631967	0.079833
6	0.102942	-0.159629	-0.487146
8	-1.835752	-1.442576	0.187899
6	-2.428028	0.914674	0.409650
6	-2.636318	-0.390231	-0.355553
6	-1.061498	1.560014	0.249532
6	-0.476724	-1.277184	0.278935
1	-2.446463	-0.264623	-1.430288
1	-2.617284	0.714540	1.471096
1	-3.665958	-0.738990	-0.241580
1	-0.711369	1.858696	2.356386

8	0.142089	-2.065892	0.968510
6	2.223062	-1.149862	-1.305225
6	1.613056	0.051697	-0.529978
1	0.384505	2.831935	1.226775
6	-0.442611	2.138968	1.341226
1	-0.884713	2.033255	-0.715041
1	1.805989	-1.225412	-2.317169
1	2.087968	-0.793498	1.427190
6	2.266063	0.124271	0.864531
1	2.030646	-2.087564	-0.778151
1	3.308401	-1.019099	-1.399433
6	1.928879	1.340758	-1.316952
1	1.871258	0.965246	1.443607
1	3.348300	0.267390	0.758219
1	-0.358647	-0.032933	-1.466544
1	1.574112	2.235168	-0.793859
1	1.471282	1.325871	-2.314661
1	3.011539	1.444931	-1.451773

%chk=T-5h

#b3lyp/6-31g* opt=(ts calcfc noeigen) iop(1/8=10) scfconver=8 freq=noraman

calculate for T-5h HF=-541.6637534

0 2

1	-2.611689	2.136761	-0.312470
6	0.194328	-0.070040	-0.420836
8	-1.966309	-1.161523	-0.578212
6	-2.370158	1.158800	0.122613
6	-2.471907	0.108283	-0.990929
6	-1.032370	1.234460	0.851290
6	-0.651325	-1.257430	-0.198114
1	-1.963833	0.447508	-1.901917
1	-3.144478	0.945327	0.870202
1	-3.518189	-0.073481	-1.249327
1	-0.912024	0.522163	1.664890
8	-0.293625	-2.293815	0.331462
1	-0.016881	0.478366	-1.336125
6	1.681359	-0.114027	-0.077558
6	-0.404773	2.455440	1.014196
1	-0.632984	3.300811	0.369626
1	0.385241	2.595841	1.744718
6	2.335717	-1.255238	-0.906772
6	1.934112	-0.376339	1.421442
6	2.348171	1.210969	-0.498759
1	2.170167	-1.107957	-1.981209
1	1.928873	-2.227223	-0.622181
1	3.419216	-1.259622	-0.734245
1	1.451465	-1.302879	1.740720
1	1.557983	0.446830	2.039667

1	3.010688	-0.464184	1.609791
1	2.216848	1.397122	-1.572338
1	3.425273	1.171530	-0.298815
1	1.934878	2.066526	0.043569

Chart S2. Computational (B3LYP/6-31G*) results of **6a** and **7a**.

%chk= 8

#B3LYP/gen OPT

calculate for **8** HF = -7313.901894

0 1

1	2.356221	0.711547	-2.761812
6	2.155826	0.637558	-1.689996
6	2.186512	2.382149	0.029632
6	0.440125	0.453820	0.106371
6	0.878749	1.840262	0.645749
6	0.684691	0.407984	-1.403529
8	2.656520	1.867634	-1.132132
8	2.772831	3.316184	0.524141
1	1.066256	-0.313728	0.583283
1	0.123027	2.574565	0.321544
1	0.080530	1.176863	-1.905434
1	0.384764	-0.562241	-1.814341
1	2.760726	-0.185741	-1.287609
6	0.984212	1.909609	2.178299
6	-1.017394	0.181562	0.478139
1	1.686551	1.156657	2.554775
1	0.014485	1.738522	2.655070

1	1.349792	2.892423	2.480152
1	-1.199972	0.278652	1.546679
53	-1.664700	-1.861295	0.009244
1	-1.704421	0.832916	-0.066330

C H O O

6-31G*

I O

3-21g*

%chk=9

#B3LYP/gen OPT

calculate for 9 HF = -7313.900938

0 1

1	-1.898518	-0.150249	-0.193725
6	0.020414	3.196204	-0.262356
6	-1.914620	1.938598	0.374787
6	0.148919	0.621289	-0.254863
6	-1.377194	0.778169	-0.450534
1	0.696872	1.997172	1.323210
8	-1.325460	3.172083	-0.075912
1	-1.719764	1.806463	1.448293
6	2.275011	2.088456	-0.141763
1	-1.602196	0.986484	-1.502571
8	0.537149	4.172346	-0.750235
1	0.606710	0.360345	-1.214782
6	0.793597	1.966763	0.225111
1	-2.990396	2.071632	0.242008
6	0.504373	-0.470603	0.756820
1	2.701754	3.006534	0.268917
1	2.399632	2.126351	-1.228526
1	2.847641	1.238051	0.243114
1	1.572695	-0.503999	0.968480
53	0.019461	-2.491557	0.058041
1	-0.042377	-0.354957	1.695368

C H O O

6-31G*

I O

3-21g*

%chk=7a-A

#B3LYP/gen OPT

calculate for **7a-A** HF=-7313.8991981

0 1

1	1.069935	1.106867	-2.933135
6	0.950495	1.003797	-1.851302
6	0.827300	2.805639	-0.174029
6	-0.700971	0.715932	0.024902
6	-0.423860	2.179739	0.456503
6	-0.469187	0.601191	-1.486906
8	1.357839	2.275747	-1.304507
1	-0.069690	-0.121630	1.929455
6	0.164251	-0.224263	0.869475
6	-1.623184	3.114039	0.184240
1	-1.184645	1.243567	-2.013086
1	1.234594	-0.062226	0.732527
1	1.673580	0.252965	-1.510429
8	1.321337	3.809766	0.283181
1	-1.750802	0.485507	0.242790
1	-0.233354	2.215900	1.535828
1	-0.643401	-0.424381	-1.829606
53	-0.153049	-2.351007	0.443644
1	-1.380564	4.130984	0.503348
1	-2.501763	2.771556	0.741653
1	-1.884742	3.143708	-0.879181

C H O O

6-31G*

I O

3-21g*

%chk=**7a-B**

#B3LYP/gen OPT

calculate for **7a-B** HF= -7313.8955253

0 1

1	-1.552644	2.084589	0.439326
6	0.220001	0.961069	-2.610871
6	-1.910993	1.208213	-1.493834
6	0.232442	0.958416	-0.088263
6	-1.300566	1.152196	-0.076773
6	0.748662	3.128246	-1.395282
8	-1.094782	0.619494	-2.528387
1	-2.125799	2.241847	-1.788021
1	1.724984	-0.637130	-0.102325
1	-1.755581	0.346090	0.506023
8	0.838522	0.711482	-3.617483
6	0.643914	-0.518280	-0.022001

6	0.843664	1.588846	-1.366307
1	-2.849197	0.652575	-1.543915
1	1.209424	3.515607	-2.309357
1	0.156396	-1.122638	-0.787969
53	0.128445	-1.479970	1.879544
1	1.906055	1.329764	-1.427907
1	1.282689	3.551165	-0.537141
1	-0.283525	3.490833	-1.358273
1	0.666959	1.465676	0.780673

C H O O

6-31G*

I O

3-21g*

%chk= 10

#B3LYP/gen OPT

calculate for 10 HF = -7313.899560

0 1

1	-1.874061	1.343064	0.579574
6	0.064449	0.975421	-2.742759
6	-1.887336	1.672004	-1.552330
6	0.141543	0.926670	-0.194999
6	-1.408290	0.919433	-0.315989
1	0.547354	2.588974	-1.474132
8	-1.289349	1.114909	-2.738084
1	-1.665344	2.746010	-1.496566
6	2.294188	1.362470	-1.625540
1	-1.768964	-0.112342	-0.395822
8	0.611977	0.461817	-3.688777
6	0.697420	-0.462260	0.115803
6	0.776615	1.513539	-1.504966
1	-2.964005	1.560036	-1.696912
53	-0.030119	-1.247161	2.030265
1	2.664280	1.947070	-2.472131
1	2.584497	0.324012	-1.804992
1	2.792103	1.718756	-0.716444
1	0.442556	1.595044	0.619792
1	1.780221	-0.464223	0.223092
1	0.405109	-1.204322	-0.629932

C H O O

6-31G*

I O

3-21g*

%chk= 11

#B3LYP/gen OPT

calculate for 11 HF = -7313.899549

0 1

1	0.673987	1.430151	-3.038441
6	0.663204	1.209405	-1.967715
6	0.721496	2.819415	-0.097623
6	-0.812671	0.754130	0.021246
6	-0.563387	2.215406	0.484602
6	-0.714049	0.751673	-1.510496
8	1.135638	2.413399	-1.326286
1	0.010708	-0.208588	1.795814
6	0.148461	-0.213766	0.716049
1	-1.370501	2.805516	0.022131
1	-1.484657	1.419273	-1.915067
1	1.197487	-0.009712	0.495043
1	1.413444	0.430603	-1.784688
8	1.336473	3.699047	0.457549
1	-1.833276	0.478663	0.313663
6	-0.633277	2.447141	1.998376
1	-0.902672	-0.248063	-1.916146
53	-0.158216	-2.310050	0.150337
1	0.205829	1.979884	2.522856
1	-1.567099	2.039068	2.401979
1	-0.593325	3.515869	2.218248

C H O O

6-31G*

I 0

3-21g*

%chk= 12

#B3LYP/gen OPT

calculate for 12 HF = -7313.899350

0 1

1	-1.471118	0.774265	1.449201
6	0.107842	3.207310	0.185112
6	-1.957594	1.960156	-0.292473
6	0.128600	0.636847	-0.016839
6	-1.352307	0.728062	0.358992
6	1.184224	1.910210	2.008500

8	-1.230963	3.178271	-0.030216
1	-2.971909	2.153328	0.066114
1	1.654607	2.861175	2.271364
1	-1.894615	-0.158022	0.010308
8	0.671077	4.276301	0.206648
1	0.194663	0.647935	-1.113822
6	0.861745	1.905314	0.496286
1	-2.001618	1.832136	-1.381879
6	0.820719	-0.633422	0.471252
1	1.878778	1.104904	2.266722
1	0.284543	1.796412	2.623542
1	1.814831	2.002753	-0.036397
1	1.893117	-0.612624	0.271344
53	0.107218	-2.443454	-0.540282
1	0.655855	-0.822630	1.532034

C H O O

6-31G*

I O

3-21g*

Chart S3. Computational (B3LYP/6-31G*) results of **6h** and **7h**.

%chk= **13**

#B3LYP/gen OPT

calculate for **13** HF = -7431.833288

0 1

1	2.965485	-0.222765	-2.292860
6	2.429294	0.006749	-1.368670
6	1.770077	2.139553	-0.423568
6	0.247193	0.034333	-0.155189
6	0.700782	1.423487	0.417874
6	0.944514	-0.280274	-1.484688
8	2.659875	1.409981	-1.144311
8	1.870358	3.345139	-0.438497

1	0.540869	-0.747685	0.552834
1	-0.149111	2.115218	0.372089
1	0.529059	0.334562	-2.295290
1	0.781398	-1.328132	-1.757405
1	2.887543	-0.570364	-0.555677
6	1.130304	1.384778	1.942915
6	-1.276539	0.014811	-0.277391
6	2.421447	0.566574	2.147645
6	-0.005907	0.761658	2.782186
6	1.360782	2.818182	2.467250
1	-1.767975	0.280236	0.657047
53	-2.082245	-1.966841	-0.768860
1	-1.629617	0.675234	-1.071835
1	3.260524	0.986435	1.581241
1	2.300065	-0.483022	1.854855
1	2.703682	0.573586	3.206662
1	2.191386	3.315795	1.962934
1	1.580186	2.784031	3.541175
1	0.469775	3.440552	2.325143
1	0.272361	0.771919	3.842367
1	-0.215443	-0.279833	2.515340
1	-0.934779	1.336741	2.683249

C H O O

6-31G*

I O

3-21g*

%chk= 14

#B3LYP/gen OPT

calculate for 14 HF = -7431.830564

0 1

1	0.828014	-1.633245	-1.539897
6	0.810722	-1.649515	-0.444781
6	2.219267	-1.696999	0.118751
6	0.069740	-0.412987	0.092891
1	0.293243	-2.568321	-0.143356
8	2.160433	-1.908117	1.538054
1	2.780794	-0.776515	-0.092959
1	-1.005289	-0.596434	0.022380
6	0.423099	-0.136173	1.606052
1	2.796556	-2.538597	-0.271469
6	0.404089	0.828717	-0.744291
6	1.186489	-1.304765	2.269021
1	1.173031	0.673678	1.609370
6	-0.791851	0.374358	2.469613

1	0.025299	1.747252	-0.305236
53	-0.495153	0.782906	-2.745530
1	1.476926	0.935198	-0.917173
8	1.035567	-1.677626	3.409567
6	-0.288774	0.931059	3.820991
6	-1.812143	-0.756843	2.718284
6	-1.518463	1.536118	1.754993
1	-1.130947	1.350350	4.384574
1	0.435390	1.741667	3.664068
1	0.182747	0.157432	4.426088
1	-2.345046	1.882961	2.385357
1	-1.951388	1.248666	0.790785
1	-0.854522	2.395203	1.595673
1	-2.661782	-0.370128	3.293079
1	-1.365545	-1.578041	3.282400
1	-2.215429	-1.157005	1.779301

C H O O

6-31G*

I O

3-21g*

%chk=15

#B3LYP/gen OPT

calculate for 15 HF = -7431.828619

0 1

1	-1.590105	2.200318	0.878365
6	-0.262638	0.711370	-2.299412
6	-2.133082	1.670621	-1.132718
6	-0.155688	0.707521	0.171950
6	-1.588100	1.296875	0.257468
1	0.276721	2.362702	-1.089903
8	-1.617296	0.829696	-2.182199
1	-1.900520	2.713515	-1.380953
6	2.081353	1.262377	-1.261870
1	-2.249663	0.578881	0.751352
8	0.186586	0.123269	-3.255059
6	-0.185596	-0.826867	0.171895
6	0.521891	1.289589	-1.121054
1	-3.216992	1.552837	-1.187866
53	-0.791403	-1.651061	2.112478
6	2.454787	2.107087	-2.503236
6	2.699138	-0.143575	-1.421216
6	2.705838	1.940108	-0.023054
1	0.421195	1.039347	1.037915
1	0.788449	-1.269789	-0.011077

1	-0.904643	-1.229356	-0.542327
1	3.759668	-0.044911	-1.682039
1	2.207669	-0.709859	-2.215322
1	2.660258	-0.720073	-0.490274
1	3.544713	2.189685	-2.585278
1	2.052578	3.125925	-2.426888
1	2.075978	1.653812	-3.421843
1	3.788065	2.044027	-0.162314
1	2.552900	1.359167	0.893395
1	2.296333	2.945660	0.139263

C H O O

6-31G*

I O

3-21g*

%chk= 16

#B3LYP/gen OPT

calculate for 16 HF = -7431.828806

0 1

1	0.776066	1.202977	-3.344768
6	0.780412	0.842079	-2.312376
6	1.171662	2.234268	-0.292453
6	-0.634163	0.412569	-0.281386
6	-0.179690	1.791688	0.299656
6	-0.625141	0.563477	-1.809999
8	1.487784	1.846378	-1.556641
1	0.103961	-0.896155	1.298901
6	0.221966	-0.749510	0.229083
1	-0.891949	2.500370	-0.153346
1	-1.299028	1.381965	-2.090454
1	1.283491	-0.636853	0.004744
1	1.390574	-0.068299	-2.282481
8	1.949070	2.974626	0.265965
1	-1.665356	0.233589	0.036986
6	-0.317177	2.038498	1.849508
1	-0.997841	-0.344869	-2.294946
53	-0.334948	-2.701455	-0.612787
6	0.856209	1.486381	2.688811
6	-1.635386	1.410924	2.352449
6	-0.410819	3.564083	2.093529
1	0.491428	4.075167	1.753795
1	-0.541571	3.765044	3.163472
1	-1.274704	3.994559	1.570165
1	-1.803933	1.700085	3.395953
1	-1.626204	0.315707	2.319293

1	-2.499031	1.759975	1.772070
1	1.804605	1.931737	2.382894
1	0.948507	0.397215	2.624752
1	0.691171	1.730103	3.745146

C H O O

6-31G*

I 0

3-21g*

Chart S4. Computational (B3LYP/6-31G*) results of 3,4-trans- and cis-dimethyl tetrahydro-2(2H)-pyranones.

%chk= 17

#B3LYP/6-31G* OPT=(CALCFC NOEIGEN Z-MATRIX) IOP(1/8=10) SCFCONVER=6

calculate 17 HF = -424.432390

0 1

1	-2.361442	0.932963	-1.863089
6	-0.088324	-0.377465	-0.774322
8	1.302731	-0.288680	1.312290
6	-0.066696	1.664986	0.673411
6	0.568632	0.855093	1.788268
6	-0.953847	0.761888	-0.190315
6	0.924114	-0.989052	0.211524
1	-0.198748	0.495094	2.486880
1	0.714513	2.128117	0.054383
1	1.295599	1.439513	2.358726
6	-1.682229	1.560687	-1.278286
8	1.464569	-2.048902	-0.002486
6	-0.903568	-1.504241	-1.427187
1	-0.237528	-2.291169	-1.785349

1	-1.488851	-1.129052	-2.271773
1	-1.596374	-1.952054	-0.704683
1	-1.712250	0.308565	0.468113
1	-0.966009	2.019111	-1.972394
1	-2.277181	2.366674	-0.833164
1	0.552788	0.070728	-1.552111
1	-0.651404	2.480794	1.117469

%chk= 18

#B3LYP/6-31G* OPT=(CALCFC NOEIGEN Z-MATRIX) IOP(1/8=10) SCFCONVER=6

calculate 18 HF = -424.431386

0 1

6	0.785441	-0.391211	-2.124690
6	0.526289	-0.238549	-0.624128
8	0.199215	1.508955	1.065369
6	-1.281313	-0.406433	1.185093
6	-0.206754	0.405715	1.895555
6	-0.737359	-1.014580	-0.133828
6	0.492037	1.239961	-0.237174
1	0.668066	-0.208625	2.149467
1	-2.122155	0.266657	0.980152
1	-0.576626	0.863152	2.816052
1	-1.507041	-0.901031	-0.907853
8	0.735250	2.153655	-0.988734
1	1.386295	-0.654718	-0.073746
6	-0.435096	-2.512247	0.020963
1	0.290315	-2.685920	0.826720
1	-0.020935	-2.942399	-0.897035
1	-1.346234	-3.069182	0.267996
1	1.714227	0.107632	-2.412266
1	-0.023600	0.066140	-2.703395
1	0.857885	-1.447288	-2.403623
1	-1.655381	-1.191231	1.853700

%chk= 19

#B3LYP/6-31G* OPT=(CALCFC NOEIGEN Z-MATRIX) IOP(1/8=10) SCFCONVER=6

calculate 19 HF = -424.429371

0 1

1	-2.067896	-0.686181	1.001517
6	0.410887	0.596973	0.752181
8	0.447427	-1.423680	-0.730093
6	-0.935319	0.539027	-1.359175
6	-0.701643	-0.959774	-1.468685
6	-0.941996	0.982780	0.111775
6	0.911633	-0.805643	0.387870

1	-0.515584	-1.263016	-2.502813
1	-1.887407	0.781953	-1.847685
1	-1.571694	-1.521979	-1.109097
6	-2.127955	0.404266	0.900546
8	1.773749	-1.355622	1.032712
6	1.538457	1.603065	0.434351
1	2.470058	1.288015	0.911765
1	-0.150307	1.073257	-1.908254
1	-3.082066	0.643477	0.415962
1	-2.153933	0.820278	1.913962
1	0.300933	0.573905	1.842876
1	1.271359	2.597005	0.810038
1	1.720725	1.686151	-0.643096
1	-1.027972	2.077382	0.140699

%chk= 20

#B3LYP/6-31G* OPT=(CALCFC NOEIGEN Z-MATRIX) IOP(1/8=10) SCFCONVER=6

calculate 20 HF = -424.430316

0 1

1	-0.283965	-0.490764	-2.575020
6	-0.555255	-0.658481	-0.417375
8	1.284000	-0.454164	1.173320
6	-0.509972	1.177403	1.360025
6	0.241794	0.036955	2.037204
6	-1.082216	0.760068	-0.025600
6	0.931175	-0.785921	-0.101239
1	-0.426490	-0.788838	2.315523
1	-1.304006	1.538411	2.024457
1	0.755745	0.370458	2.941684
1	0.304372	1.910905	-1.263071
8	1.780643	-1.153714	-0.876862
1	-1.126076	2.811901	-0.737078
1	-1.923429	-0.967356	-2.074620
1	-0.581957	-2.129701	-2.009385
6	-0.855646	-1.082200	-1.855523
1	-2.173261	0.669167	0.052866
1	-1.264525	1.621196	-2.036046
1	-1.060969	-1.367833	0.255574
6	-0.774709	1.831961	-1.080621
1	0.196394	2.006772	1.232226

%chk= 21

#B3LYP/6-31G* OPT=(CALCFC NOEIGEN Z-MATRIX) IOP(1/8=10) SCFCONVER=6

calculate 21 HF = -424.430071

0 1

6	0.629673	0.907831	2.070293
6	0.549406	0.671202	0.558361
8	0.611922	-1.275704	-0.995968
6	-0.681078	0.766011	-1.592769
6	-0.441143	-0.720945	-1.811405
6	-0.789672	1.086720	-0.094173
6	0.966858	-0.764255	0.214573
1	-0.145760	-0.931914	-2.843091
1	-1.594051	1.053959	-2.129492
1	-1.349337	-1.298745	-1.601992
6	-2.018491	0.437471	0.562810
8	1.672474	-1.431875	0.933279
1	1.327480	1.290777	0.082998
1	-1.944508	-0.656422	0.593424
1	0.144848	1.341887	-2.030241
1	1.637067	0.699098	2.436137
1	-0.057416	0.255523	2.617840
1	0.377577	1.948735	2.303891
1	-2.931570	0.694983	0.013185
1	-2.145443	0.783537	1.593032
1	-0.887376	2.174994	0.019679

%chk= **22**

#B3LYP/6-31G* OPT=(CALCFC NOEIGEN Z-MATRIX) IOP(1/8=10) SCFCONVER=6

calculate **22** HF = -424.429664

0 1

1	-0.605530	2.899793	-0.209757
6	0.328356	0.331395	0.825434
8	0.251834	-1.692846	-0.647320
6	-1.002600	0.346542	-1.301325
6	-0.867607	-1.165122	-1.387175
6	-0.999855	0.778321	0.169020
6	0.729373	-1.109604	0.484331
1	-0.713333	-1.506632	-2.414444
1	-1.936843	0.642726	-1.795209
1	-1.774555	-1.650596	-1.002478
1	2.436859	0.817331	0.982986
8	1.529609	-1.720623	1.153063
6	1.543450	1.233595	0.510351
1	1.388624	2.244282	0.899081
1	-0.184067	0.832933	-1.847684
1	-1.244815	2.561621	1.407600
1	-2.315319	2.499756	-0.001123
1	0.203931	0.333723	1.914847
1	1.733650	1.307928	-0.566357
1	-1.804882	0.217115	0.669152
6	-1.303661	2.269503	0.352271

%chk= 23

#B3LYP/6-31G* OPT=(CALCFC NOEIGEN Z-MATRIX) IOP(1/8=10) SCFCONVER=6

calculate 23 HF = -424.426249

0 1

1	-2.554474	0.863001	-1.678085
6	-0.324706	-0.541043	-0.700485
8	1.712915	0.110637	0.519057
6	-0.426039	1.282976	1.080314
6	0.832657	0.545599	1.574576
6	-0.811266	0.888935	-0.363443
6	1.190743	-0.602019	-0.518066
1	0.562197	-0.332416	2.172232
1	-1.248082	1.053234	1.770336
1	1.455681	1.187328	2.201032
1	-0.580863	-2.645399	-0.217919
8	1.934712	-1.193242	-1.263162
6	-1.032473	-1.685894	0.053445
1	-2.575207	2.157726	-0.470783
1	-2.930944	0.496525	0.016310
1	-0.475014	-0.718776	-1.771119
6	-2.302263	1.109487	-0.639928
1	-2.091813	-1.726229	-0.218632
1	-0.972943	-1.582445	1.141925
1	-0.253540	1.552932	-1.038210
1	-0.275929	2.367120	1.127276

FX-60
房欣通

ppm

200

180

160

140

120

100

80

60

40

20

7c

FX-0116-1

FX-0712-1

ppm 180 160 140 120 100 80 60 40 20

7f

77
77.099
76.782

36 558
30
29

FX 0404

高放電

TX-0309-3

PPM

7g