Homocoupling versus Reduction of Radicals: An Experimental and Theoretical Study of Ti(III)-mediated Deoxygenation of Activated Alcohols

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Supporting Information

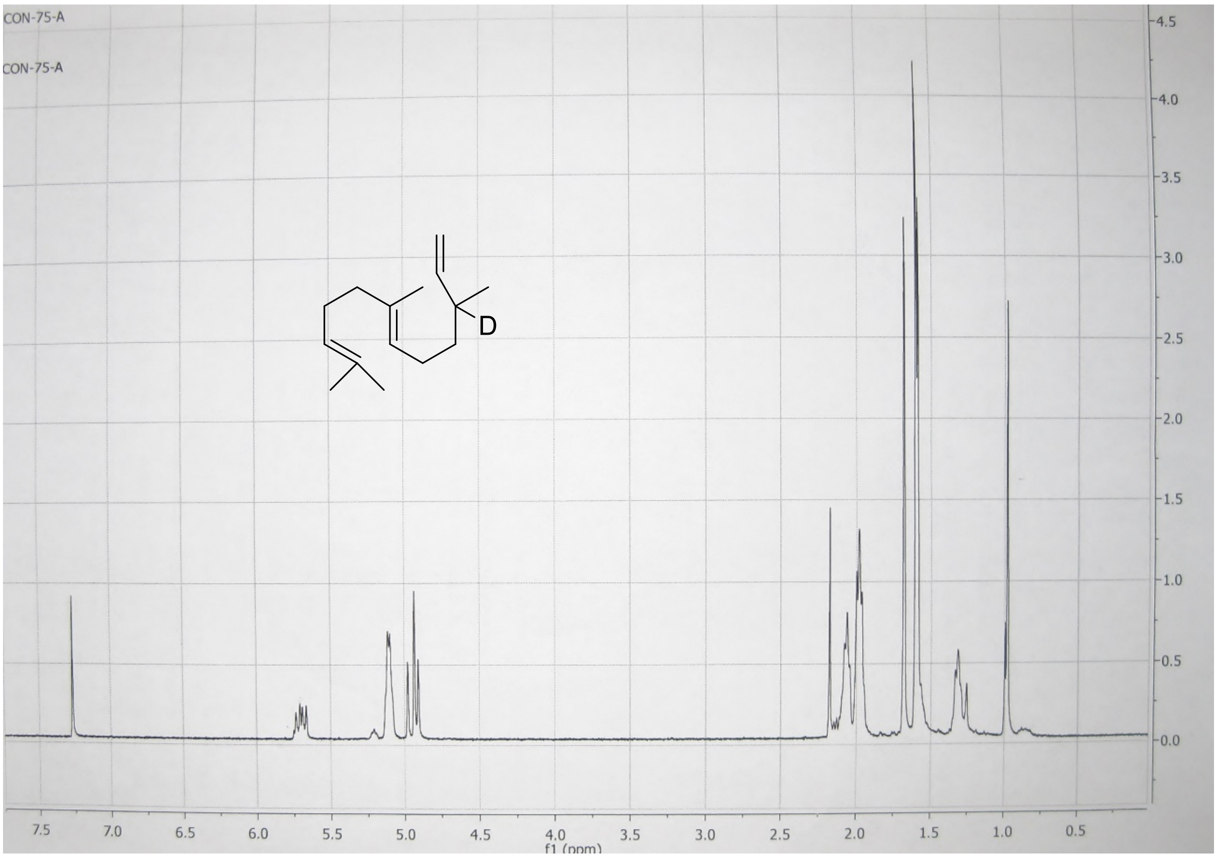
1. - GENERAL DETAILS

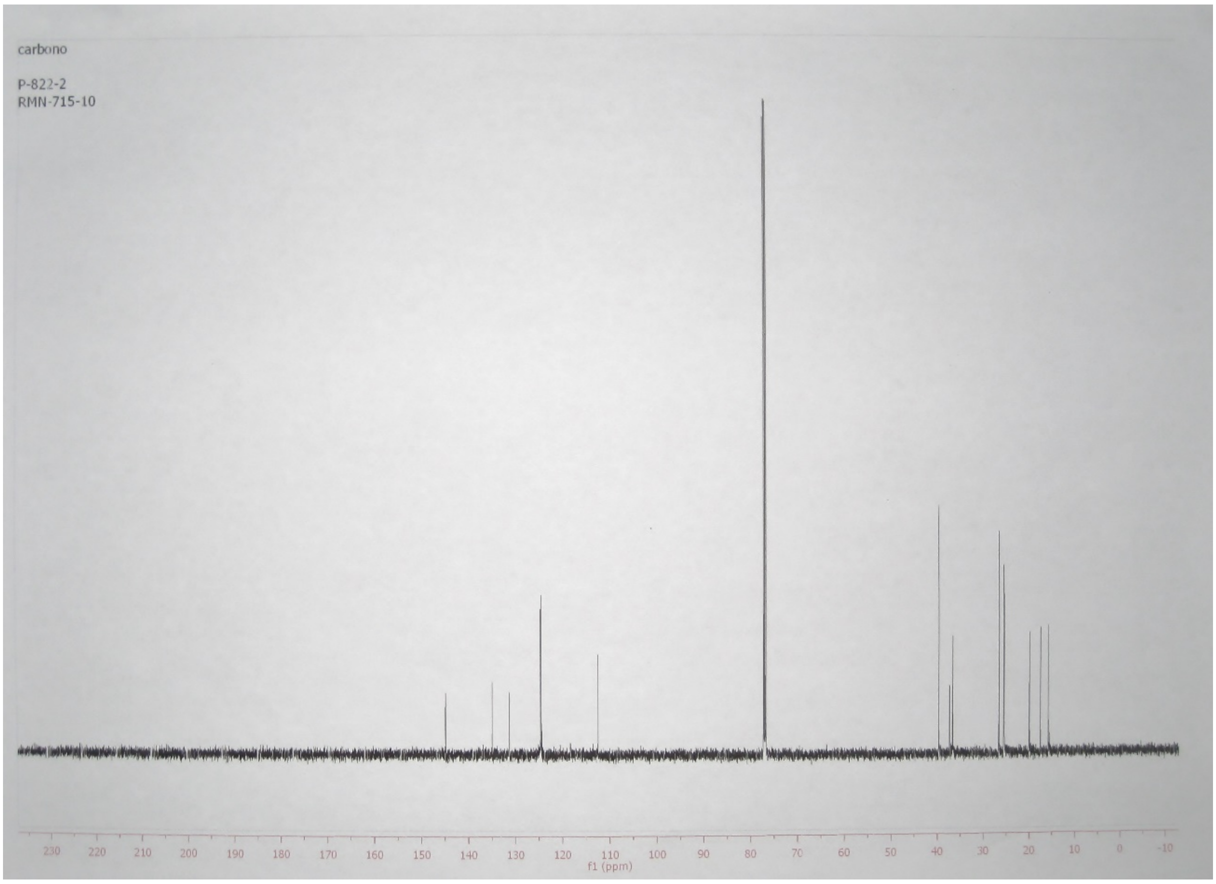
The solvents used were purified according to standard literature techniques and stored under Argon. THF was freshly distilled immediately prior to use from sodium/benzophenone and strictly deoxygenated for 30 min under Argon for each of the Cp_2TiCl_2/Mn reactions. Reagents were purchased at the higher commercial quality and used without further purification, unless otherwise stated. Yields refer to chromatographically and spectroscopically (^{1}H NMR) homogeneous materials, unless otherwise stated. NMR spectra were performed either with ^{1}H 500 MHz/^{13}C 125 MHz, ^{1}H 400 MHz/^{13}C 100 MHz, or^{1}H 300 MHz/^{13}C 75 MHz spectrometers. The accurate mass determination was carried out with an AutoSpec-Q mass spectrometer arranged in an EBE geometry and equipped with a FAB (LSIMS) source. The instrument was operated at 8 KV of accelerating voltage and Cs^+ were used as primary ions. Silica gel (35–70 μm) was used for flash column chromatography. Reactions were monitored by thin layer chromatography (TLC) carried out on 0.25 mm silica gel plates (60F–254) using UV light as the visualizing agent and solutions of phosphomolybdic acid in ethanol or acidic mixture of anisaldehyde and heat as developing agents. All air- and water-sensitive reactions were performed in flaks flame-dried under a positive flow of Argon and conducted under an Argon atmosphere. The following abbreviations were used to explain the multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, m = multiplet, pent = pentet, hex = hexet, br = broad.

Yields corresponding to experiments carried out for the study and optimization of the reduction/homocoupling methodology (Table 1 and Table 2) were calculated by yields and ^{1}H NMR integrals in the case of the mixture of **2**–**3** or **9**–**10** obtained from the first silica gel flash chromatography.

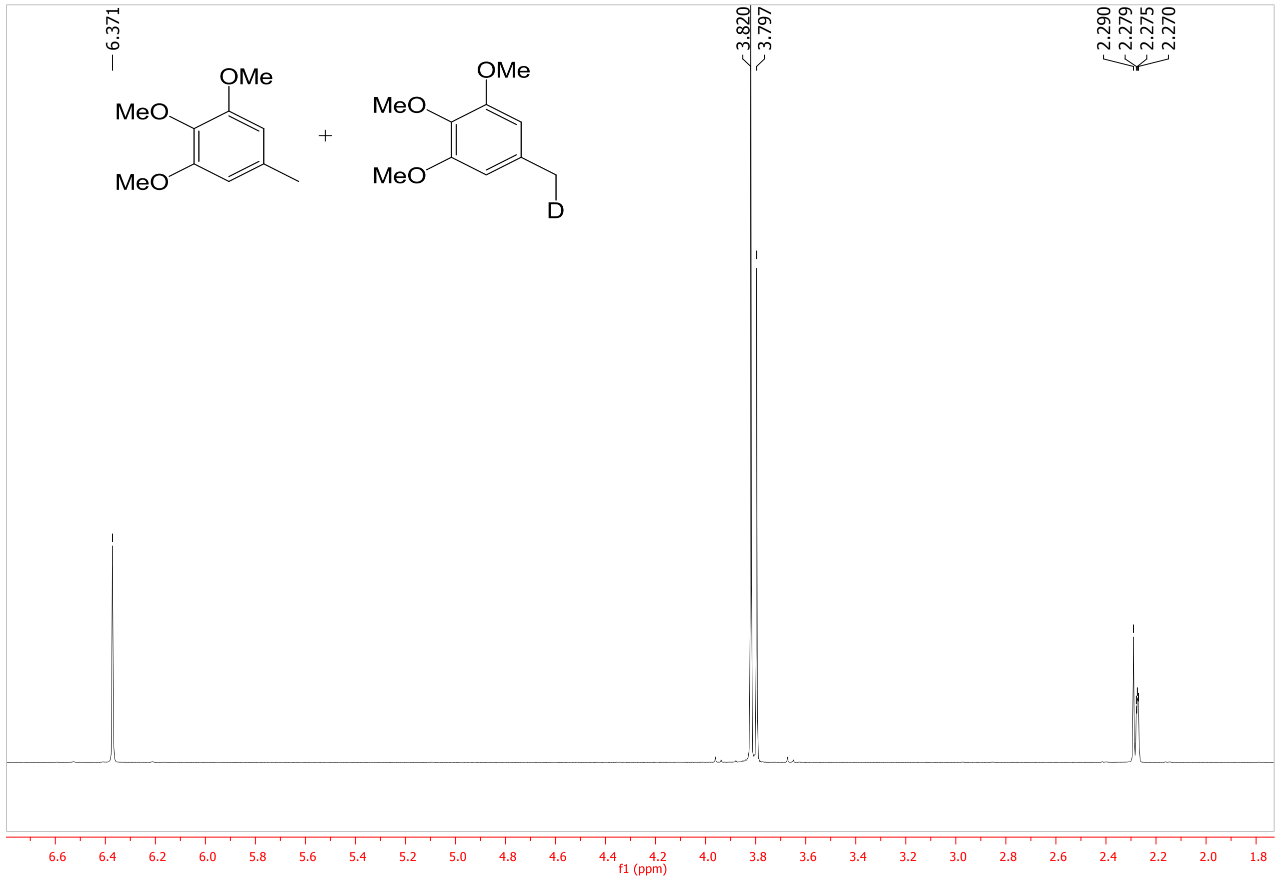
2. - SPECTROSCOPIC DATA FOR DEUTERATED DERIVATIVES OF 2 AND 9

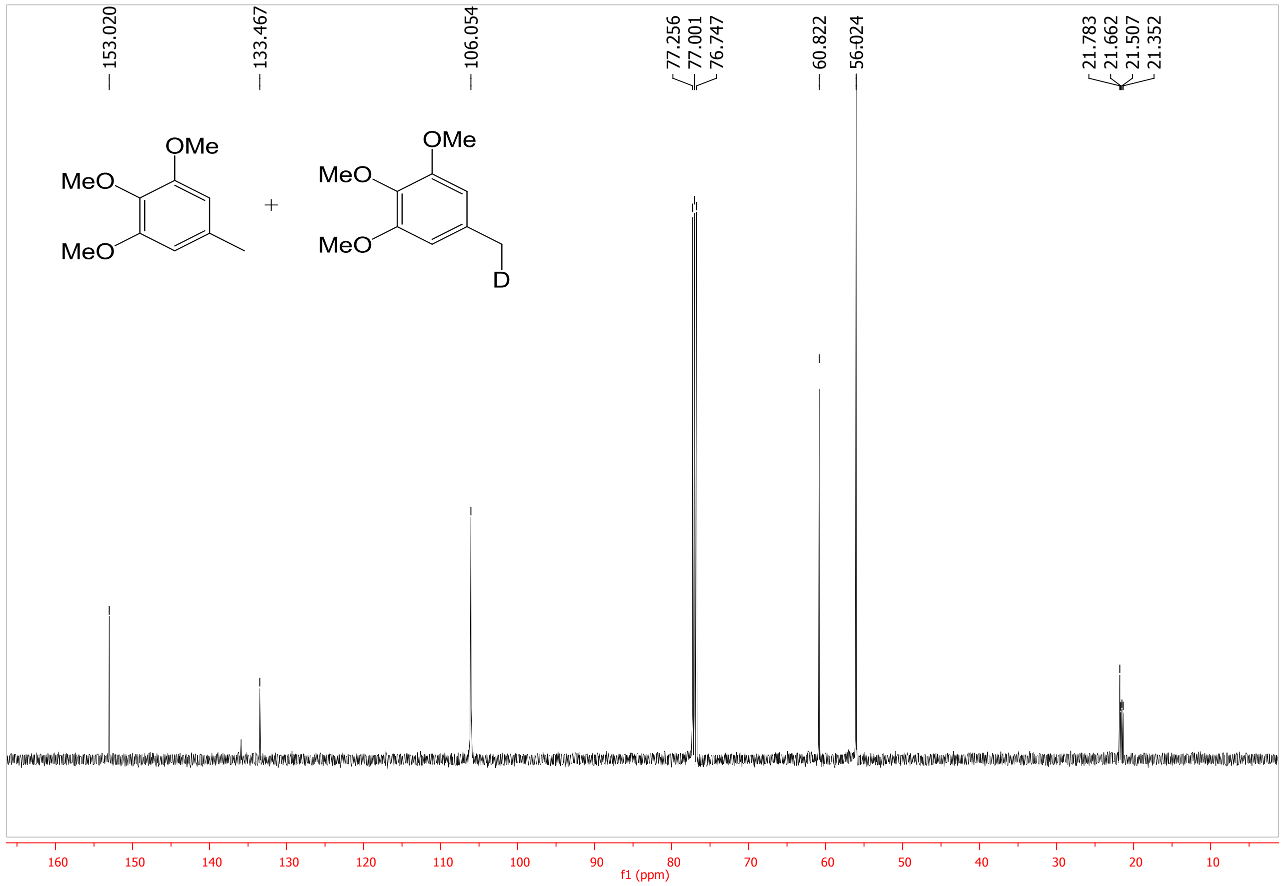
2.1.^{1}H and ^{13}C NMR spectra of C–3 deuterated compound 2





2.2. ^{1}H and ^{13}C NMR spectra of deuterated compound 9

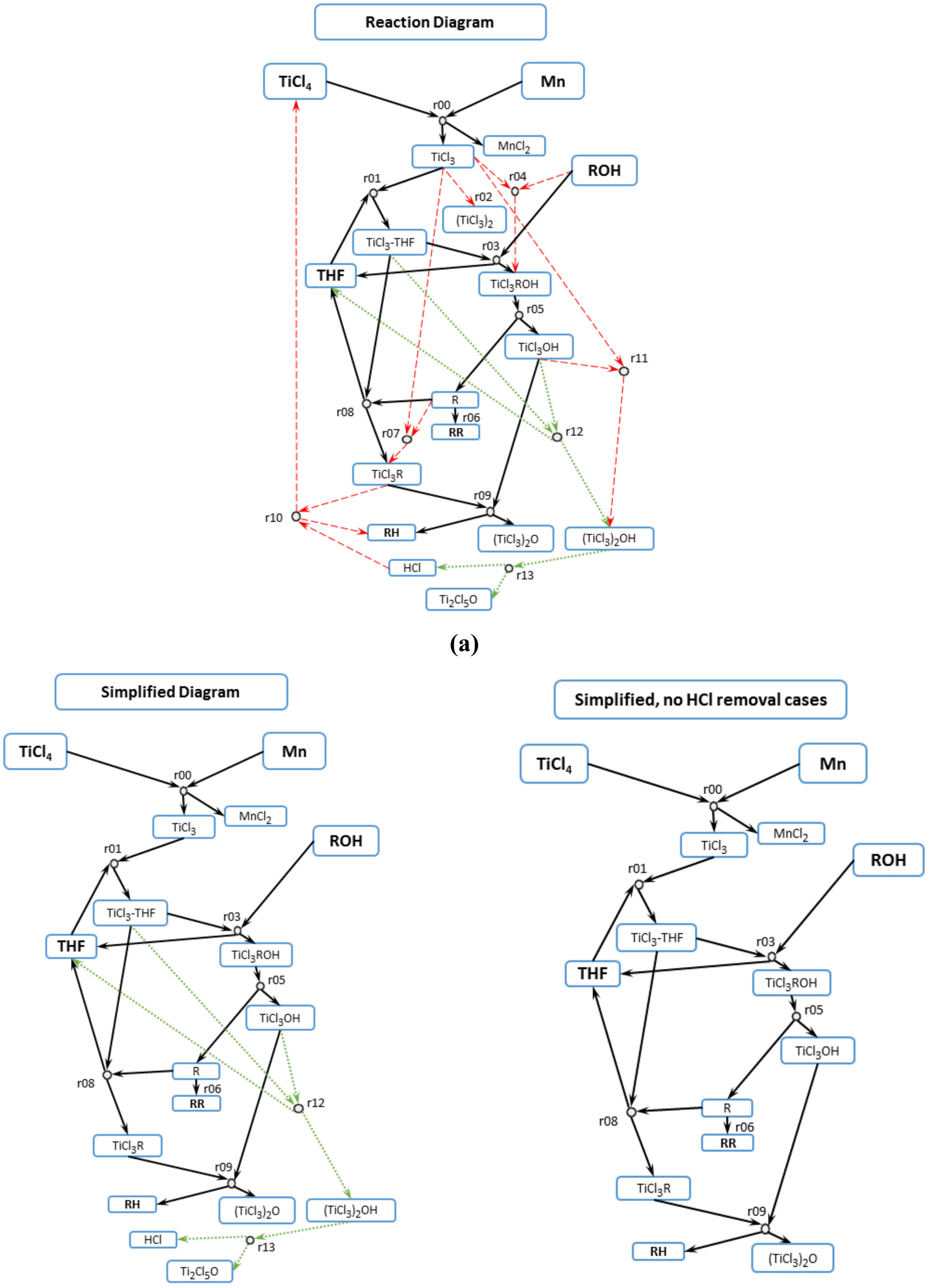




3. - COMPUTATIONAL DETAILS.-

3.1. Reaction set simulated with COPASI

3.1.1 **Scheme 1**. (**a**) Complete reaction diagram, (**b**) simplified reaction diagram, and (**c**) simplified reaction diagram (no HCl removal cases) of the reactions listed in Table 3. The reactions listed in Table 3 with a negligible contribution have been omitted in both Simplified Diagrams **b** and **c**.



(a)

(b)

(c)

3.1.2. **Simulations**[1]

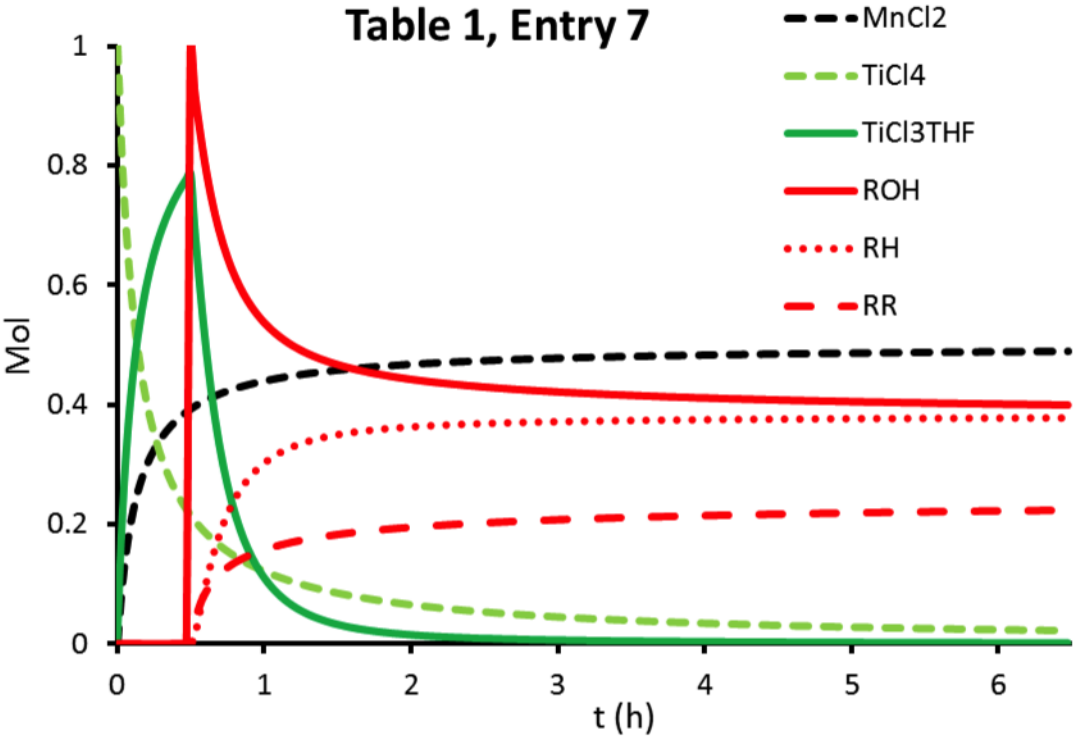
The reaction set listed in Table 3 and shown in the Reaction Diagram above was implemented in COPASI (Complex Pathway SImulator). Models (the Reaction Diagram in our case) are defined as chemical reactions between molecular species. The kinetics of a model is determined by the rate law associated with individual reactions. For example, the concentration of R–H evolves with time as (see Reaction Diagram and r09, r10 in Table 3):

$$d[RH]/dt = k09*[TiCl_3R]*[TiCl_3OH] + k10*[TiCl_3R]*[HCl]$$

with $k09 = A*\exp(-b09/RT)$, $k10= A*\exp(-b10/RT)$ and $A=4*10^7\ M^{-1}s^{-1}$.

The complete system of differential equations is solved numerically by COPASI using the barriers listed in Table 3 and the $TiCl_4$ and Mn initial concentrations (per mol of R–OH) given in Table 1. Thus, for example for Entry 7 of Table 1, we get the time evolution for some representative species represented below in 3.1.3:

3.1.3. **Simulation for Entry 7 of Table 1**



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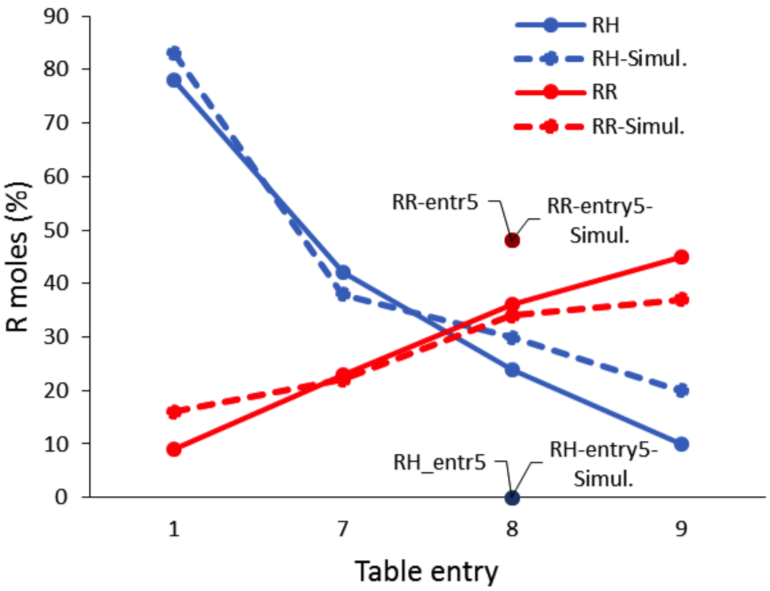
[1] For other examples of systems modeled with Copasi software, see: (a) D. A. Colby, R. G. Bergman and J. A. Ellman, *J. Am. Chem. Soc.*, 2008, **130**, 3645–3651; (b) M. P. Watson, L. E. Overman and R. G.Bergman, *J. Am. Chem. Soc.*, 2007, **129**, 5031–5044; (c) R. Ghosh, X. Zhang, P. Achord, T. J. Emge, K. Krogh-Jespersen and A. S.Goldman, *J. Am. Chem. Soc.*, 2007, **129**, 853–866.

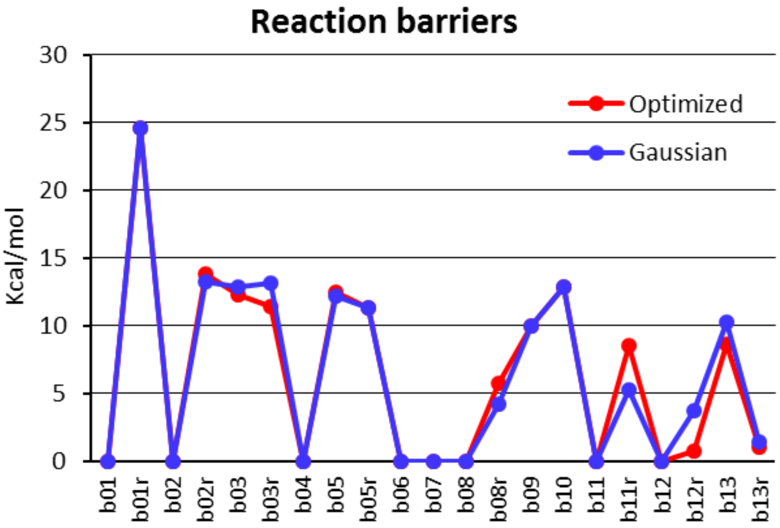
The species not plotted are below 0.02 mol except for THF, Mn, $(TiCl_3)_2O$ (almost equal to R–H) and $TiCl_3OH$ (almost equal to R–R). Refer to the above Figure and to the Simplified Reaction Diagram for the following comments. Before R–OH is added (first half hour), $TiCl_4$ and Mn decrease to form $MnCl_2$ and $TiCl_3$. However, $TiCl_3$ is immediately solvated to $TiCl_3THF$ (with two THF molecules, actually) as seen in the figure. After about half an hour, R–OH is added and interacts slowly (non-negligible forward and reverse barriers b03, b03r) with $TiCl_3THF$ to release $R^\bullet$ and $TiCl_3OH$. $R^\bullet$ proceeds immediately through r08, r09 to form R–H while $TiCl_3OH$ is partially spent to protonate $R^\bullet$ through r09. For these particular conditions (Entry 7) the reaction stops because all the $TiCl_3THF$ (and $TiCl_4$) available has been consumed. Reactions r12 and r13 have a negligible contribution and can also be deleted from the Simplified Reaction Diagram (see Figure above) except when the generated HCl is extracted from the media (Entry 5).

3.1.4. **Graph showing a comparison between experimental and simulated values of R–H and R–R of Table 1, entries 1, 7, 8, 9 and 5.**



Entries 1, 7, 8, 9 are ordered by decreasing molarity of $TiCl_4$ and Mn, while entry 5 has the same molarities as entry 8 but the HCl gas generated is removed from the reaction media. The agreement between experiment and simulation is very good. In addition, the parameter (barrier energies) optimization with COPASI can be done using only entries 1, 7, 8 and 9 (using the complete Reaction Diagram) and then the behaviour for entry 5 (HCl removal) is correctly predicted by the simulator by the mechanisms described in the paper (switching the $TiCl_3THF$ flux from r08 to r12). This reinforces the plausibility of the model.

3.1.5. **Graph showing a comparison between the barrier values obtained with Gaussian09 and optimized with COPASI.**



The reaction barriers calculated with Gaussian need only be slightly fine-tuned by Copasi to provide a remarkably close agreement with the experimental results. This is a valuable feature since it would be difficult to find the large number of parameter values using just a blind optimization within Copasi. Notice, however, that the constraints imposed by the limited experimental conditions tested is not enough to establish a unique set of barrier values. In any case, the use of a set of parameters obtained with an *ab-initio* program increases the prediction capabilities of the model since it is founded on physically-based parameters. In fact, the model thus developed can later be used to design further experiments or tests (as the HCl gas removal effect).

3.2. **Gaussian09: Methodology**

Geometry optimizations and energy calculations were performed with GAUSSIAN 09[2] using DFT[3] at the b3lyp/6-31+g(d,p)[4] level of theory *in vacuo*. To simulate the solvent effect used in the experimental reactions (tetrahydrofuran), a single point calculation was performed at the same level described before, using the SMD continuum model.[5] Transition state structures were optimized as saddle points at the same level of calculation. A vibrational analysis was performed at the same level of theory in order to determine the zero-point vibrational energy and to characterize each stationary point as a minimum or transition state structure. Transition states were identified by the presence of a single imaginary frequency that corresponds to the expected motion along the reaction coordinate. The reported energies are expressed in Hartrees (au) and include zero-point energy corrections. The same energies expressed in Kcal/mol as relative energies appear in the Scheme **4** in the paper. To verify that the TSs correspond to the expected reactant and product wells, intrinsic reaction coordinate (IRC)[6] calculations were performed at the same level b3lyp/6-31+g(d,p). In the IRC plots, energies do not include zero point energy corrections. Structural drawings were produced by Spartan08.[7]

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[2] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, D. J. Fox in Gaussian 09, Revision B.01, Vol. Gaussian, Inc., Wallingford, CT, 2009.

[3] (a) Lynch, B. J.; Zhao, Y.; Truhlar, D. G. *J. Phys. Chem. A* 2003,**107**, 1384-1388; (b)W. Koch and M.C. Holthausen, *A Chemist's Guide to Density Functional Theory*, Wiley-VCH, Weinheim, Germany, 2nd, 2000, pp. 117–259; (c) R. G. Parr and W. Yang,*Density Functional Theory of Atoms and Molecules*, Clarendon Press, Oxford, UK, 1989**.**

[4] (a) P. J. Stephens, F. J. Devlin, C. F. Chabalowski and M. J. Frisch, *J. Phys. Chem.*, 1994, **98**, 11623–11627; (b) K. Kim and K. D. Jordan, *J. Phys. Chem.*, 1994, **98**, 10089–10094; (c) A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 5648–5652; (d) A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 1372–1377; (e) C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B*, 1988, **37**, 785–789.

[5] A. V. Marenich, C. J. Cramer and D. G. Truhlar, *J. Phys. Chem. B*, 2009, **113**, 6378–6396.

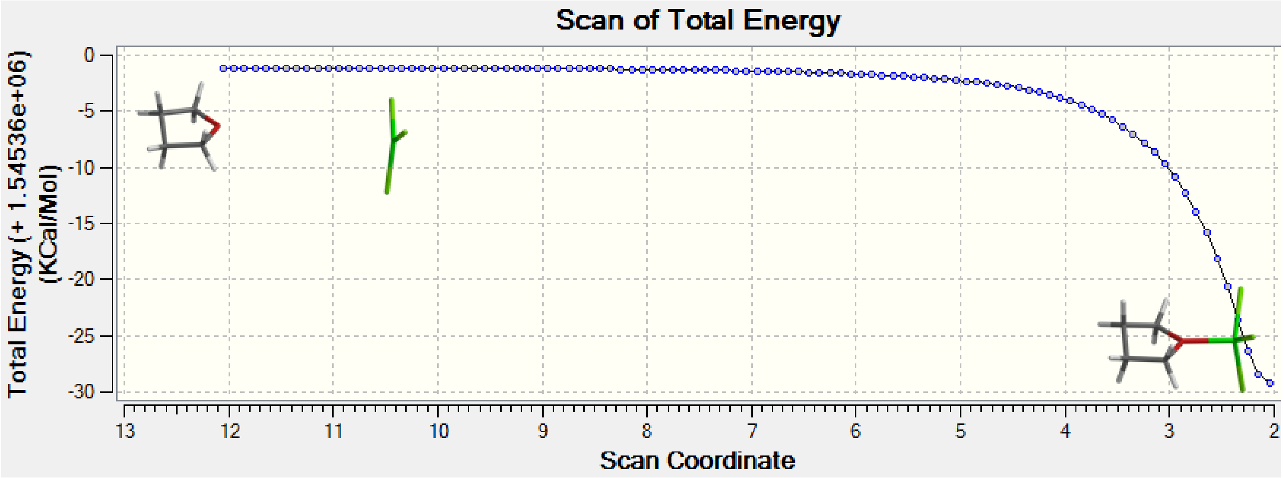
[6] (a) C. Gonzalez and H. B. Schlegel, *J. Chem. Phys.*, 1989, **90**, 2154–2161; (b) C. Gonzalez and H. B. Schlegel, *J. Chem. Phys.*, 1991, **95**, 5853–5860; (c) H. P. Hratchian and H. B. Schlegel, *J. Chem. Phys.*, 2004, **120**, 9918–9924; (d) H. P. Hratchian and H. B. Schlegel, *J. Chem. Theory Comput.*, 2005, **1**, 61–69.

[7] Spartan`08. Wavefunction, Inc., Irvine, CA.

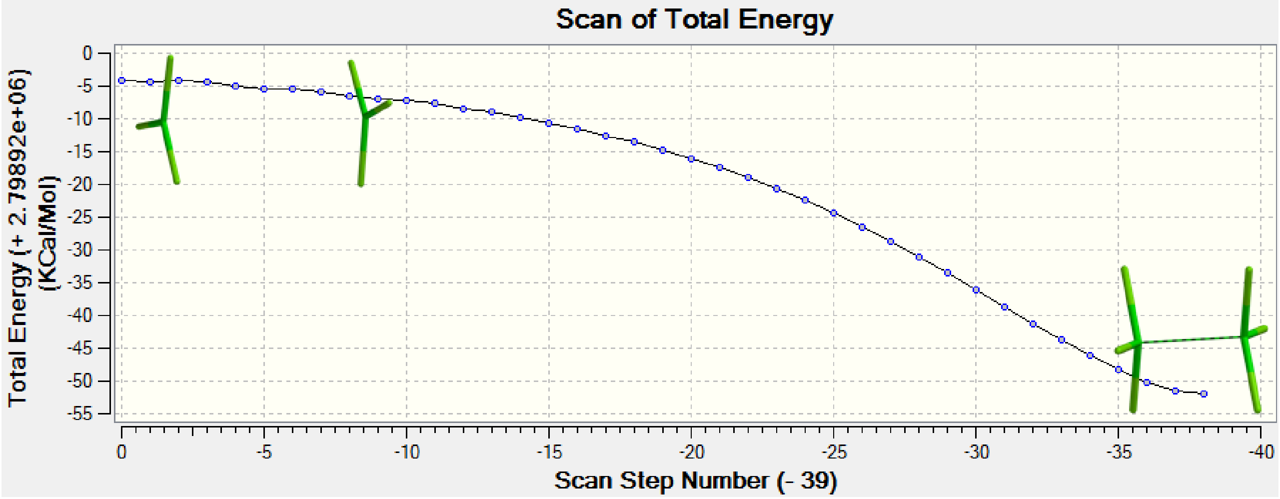
3.3. Relaxed Potential Energy Surface Scans in *in vacuo* [b3lyp/6-31+g(d,p)].

The Relaxed Potential Energy Surface Scans and the IRC plots *in vacuo*, do not include zero point energy corrections. To calculate the barriers in Table 2, the solvent effects (THF) using the SMD continuum model, has been considered.

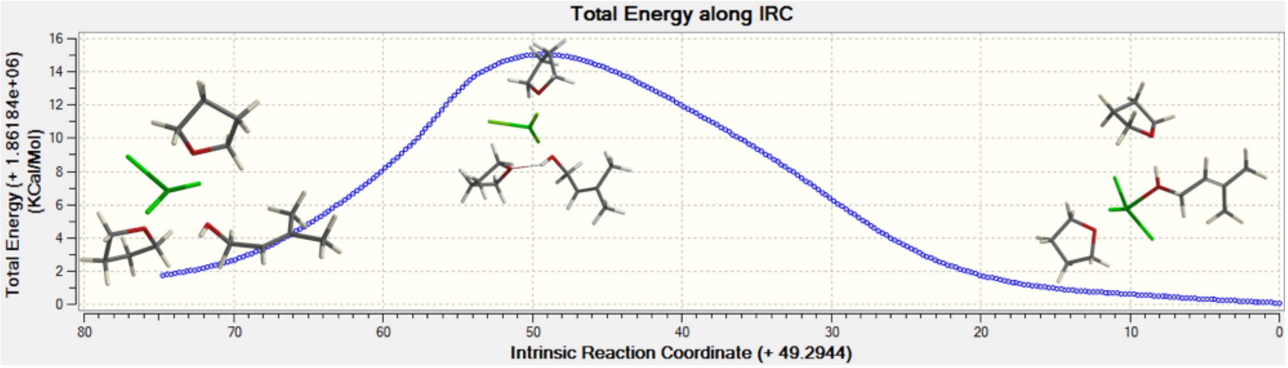
3.3.1. **Relaxed Potential Energy Surface Scans for r01 *in vacuo* (b3lyp/6-31+g(d,p))**



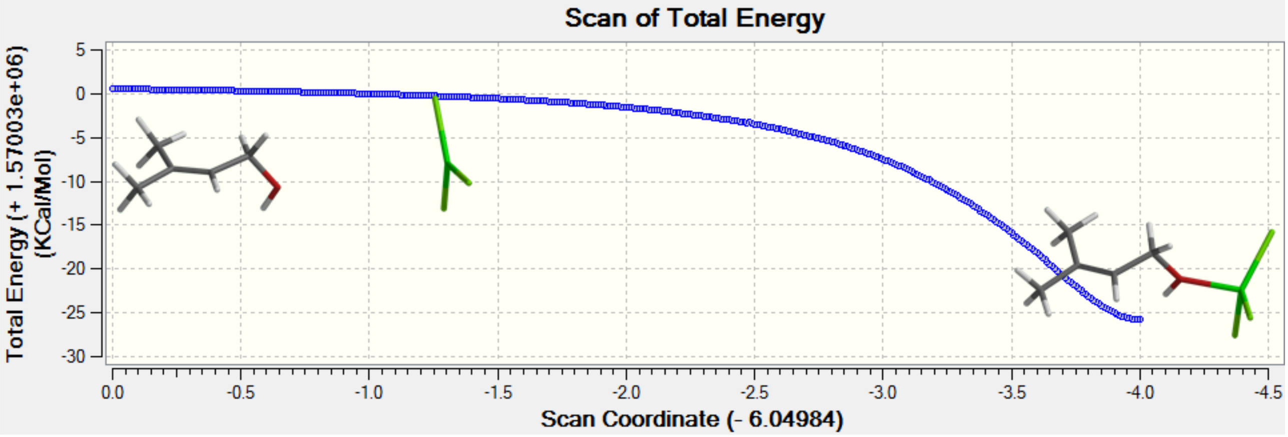
3.3.2. **Relaxed Potential Energy Surface Scans for r02 *in vacuo* (b3lyp/6-31+g(d,p))**



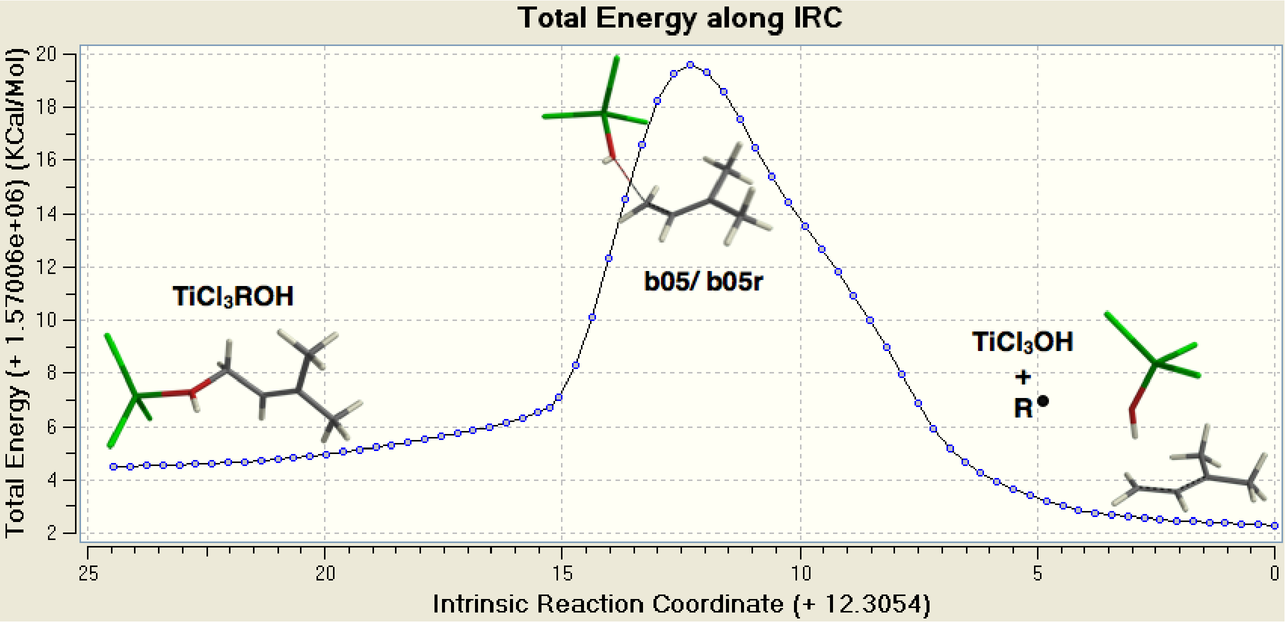
3.3.3. **Plot of IRC of r03 *in vacuo* (b3lyp/6-31+g(d,p))**



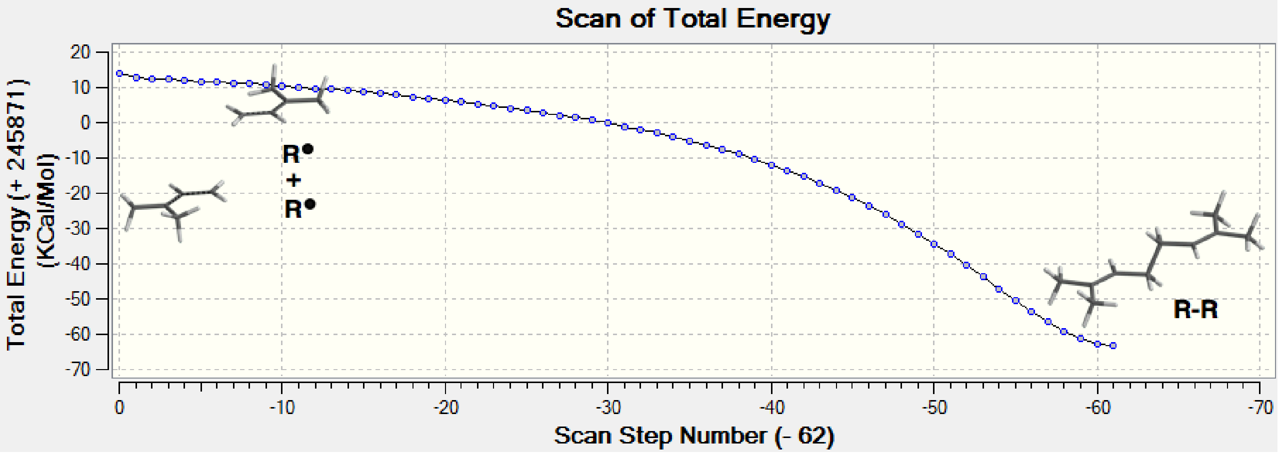
3.3.4. **Relaxed Potential Energy Surface Scans for r04 *in vacuo* (b3lyp/6-31+g(d,p))**



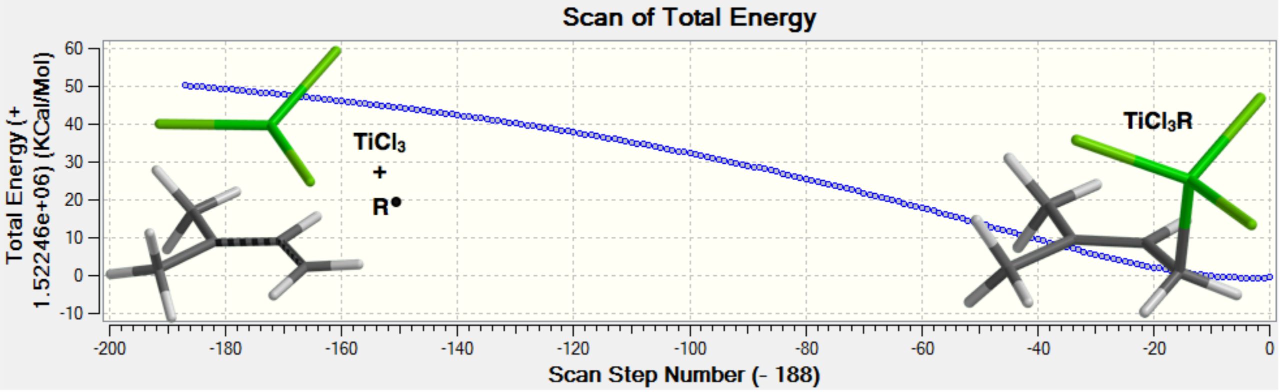
3.3.5. **Plot of IRC for r05 *in vacuo* (b3lyp/6-31+g(d,p))**



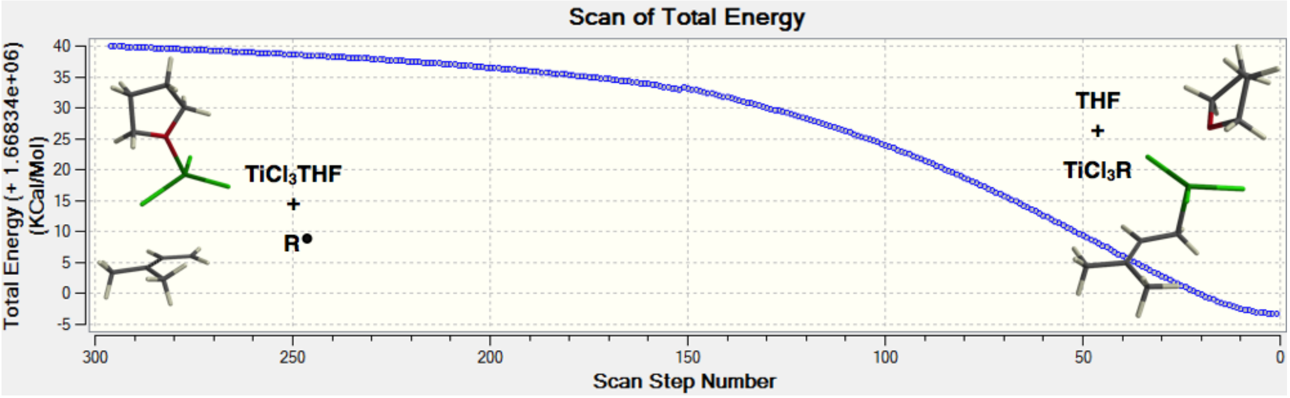
3.3.6. **Relaxed Potential Energy Surface Scans for r06 *in vacuo* (b3lyp/6-31+g(d,p))**



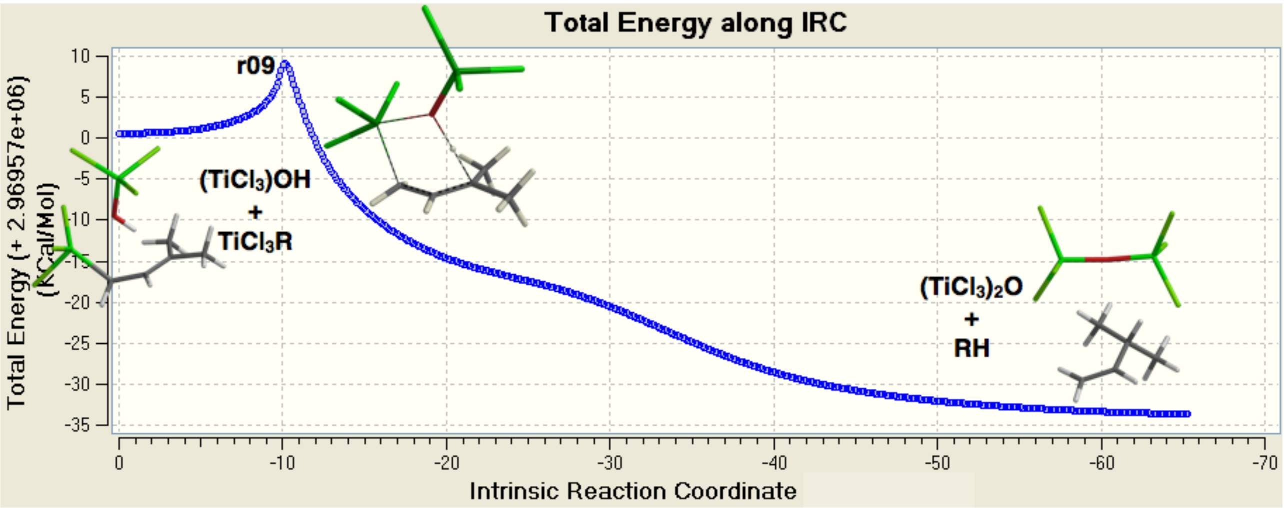
3.3.7. **Relaxed Potential Energy Surface Scans for r07 *in vacuo* (b3lyp/6-31+g(d,p))**



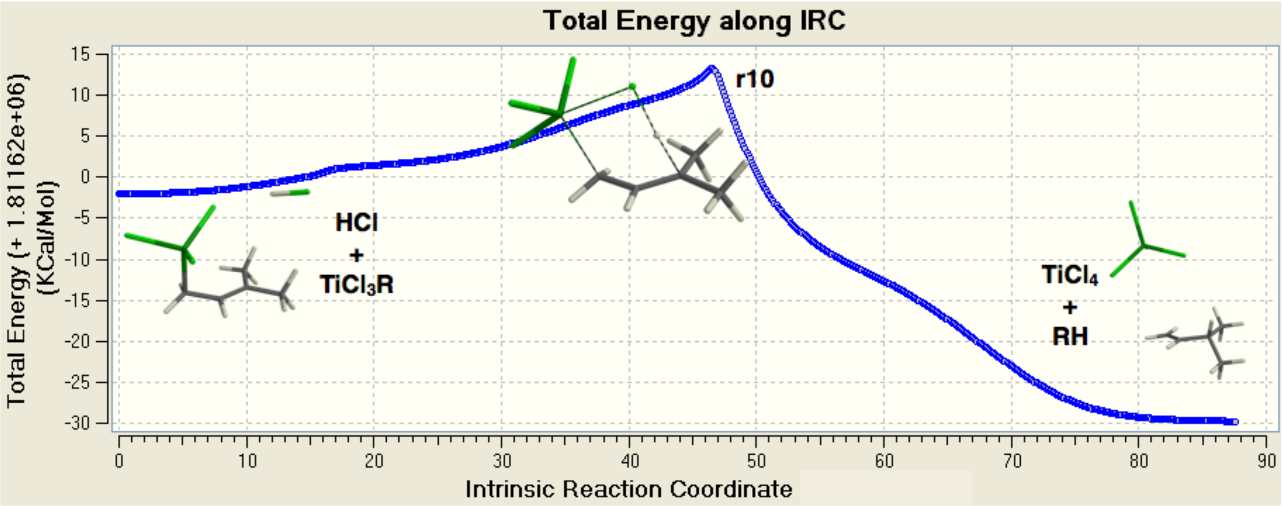
3.3.8. **Relaxed Potential Energy Surface Scans for r08 *in vacuo* (b3lyp/6-31+g(d,p))**



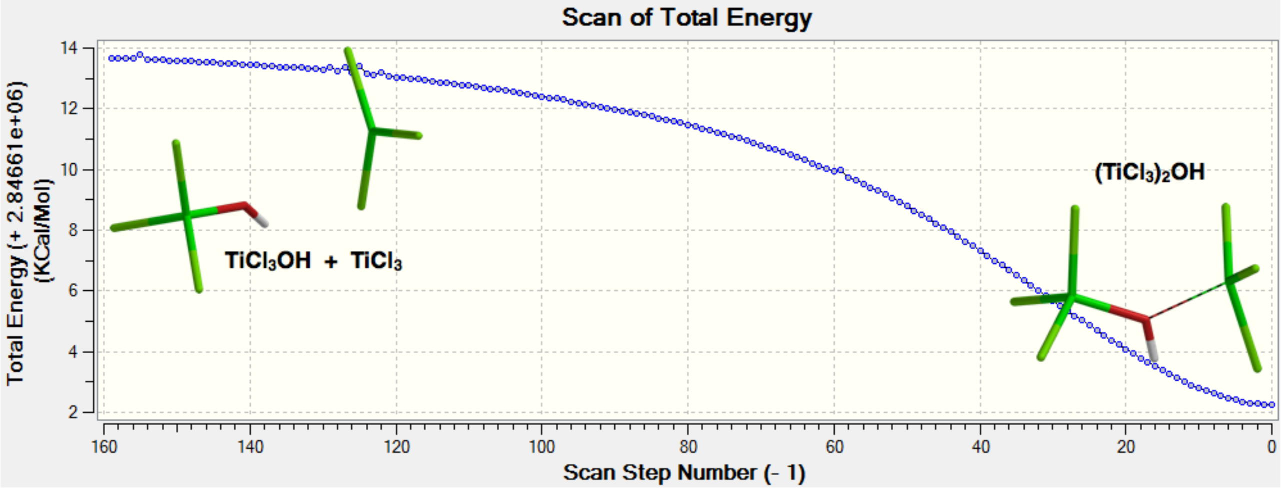
3.3.9. Plot of IRC for r09 *in vacuo* (b3lyp/6-31+g(d,p))



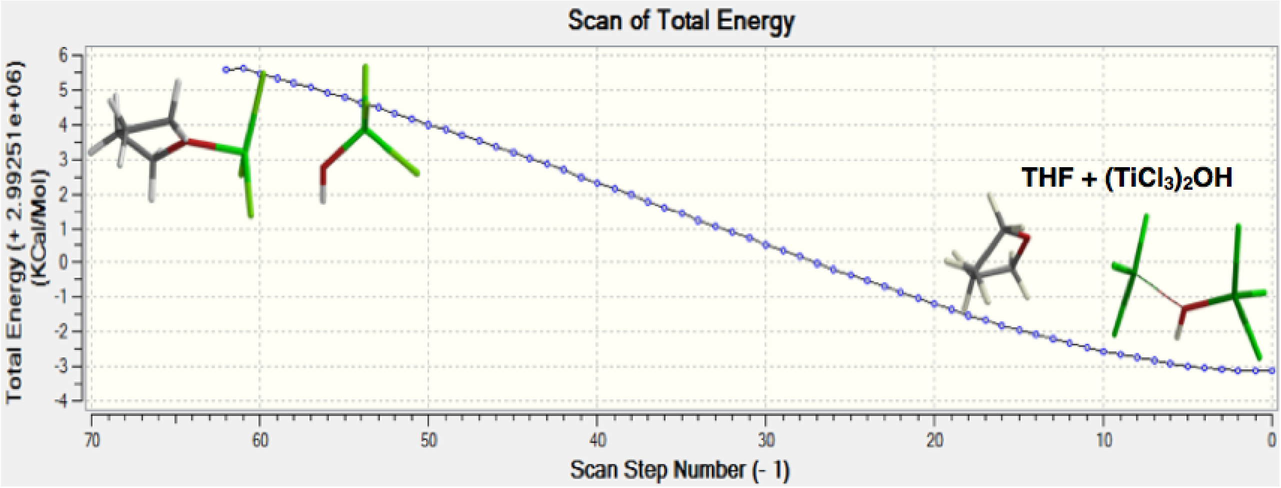
3.3.10. Plot of IRC for r10 *in vacuo* (b3lyp/6-31+g(d,p))



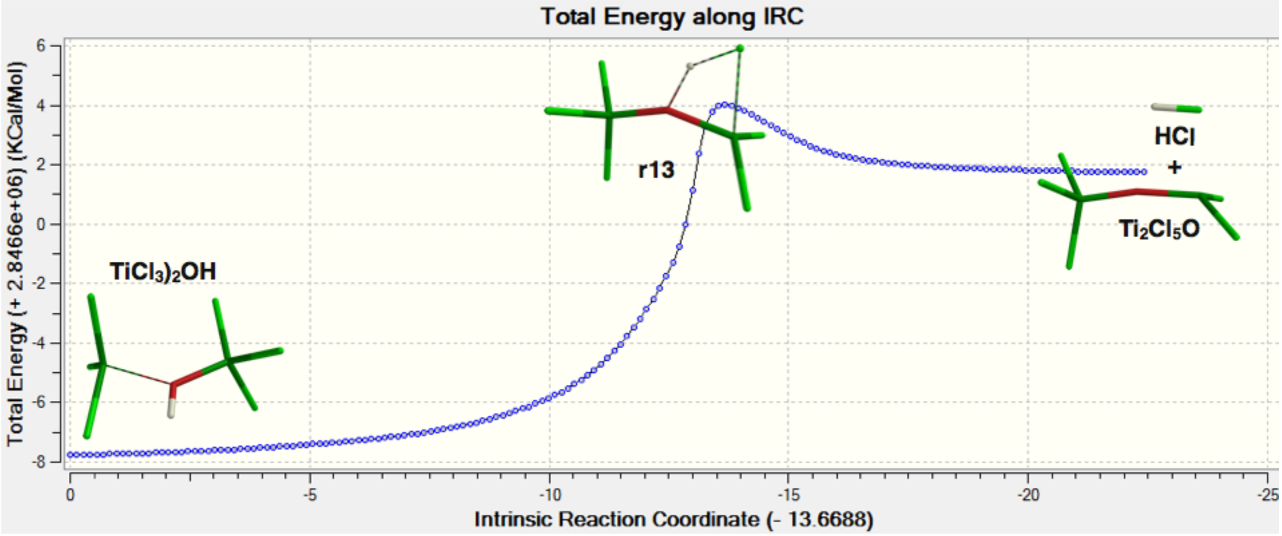
3.3.11. Relaxed Potential Energy Surface Scans for r11 *in vacuo* (b3lyp/6-31+g(d,p))



3.3.12. **Relaxed Potential Energy Surface Scans for r12 *in vacuo* (b3lyp/6-31+g(d,p))**

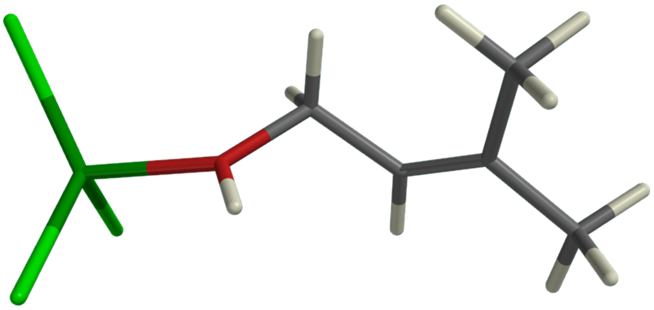


3.3.13. **Plot of IRC of r05 for r13 *in vacuo* (b3lyp/6-31+g(d,p))**



3.4.- CARTESIAN COORDINATES, ENERGIES AND IRC PLOTS:

3.4.1. Structure, Cartesian Coordinates and Energies of **$TiCl_3ROH$ (I)**



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--------------------------------------------------------------

#freq b3lyp/6-31+g(d,p) scrf=(smd, solvent=thf)//# opt freq b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 2
--------------------------------------------------------------
6       2.636426000    -0.465727000    -0.475430000
6       3.840741000    -0.017536000    -0.066661000
1       2.482334000    -1.540368000    -0.557845000
6       1.453058000     0.364945000    -0.838617000
1       1.661495000     1.433621000    -0.903296000
1       0.992282000     0.035327000    -1.772293000
8       0.380705000     0.191733000     0.165441000
1       0.742751000     0.158824000     1.067452000
22     -1.650369000    -0.031817000     0.002323000
17     -1.940775000    -1.952774000    -1.125269000
17     -1.763600000    -0.221184000     2.284996000
17     -2.411619000     1.906081000    -0.835252000
6       4.222260000     1.432862000     0.096193000
1       4.598628000     1.610507000     1.110978000
1       5.041607000     1.686538000    -0.587911000
1       3.404567000     2.132082000    -0.086310000
6       4.944437000    -0.994905000     0.253903000
1       5.815729000    -0.817064000    -0.389083000
1       5.286680000    -0.865060000     1.288287000
1       4.626759000    -2.032216000     0.122987000
--------------------------------------------------------------
 Zero-point correction=                           0.145232 (Hartree/Particle)
 Thermal correction to Energy=                    0.158369
 Thermal correction to Enthalpy=                  0.159313
 Thermal correction to Gibbs Free Energy=         0.101781
 Sum of electronic and zero-point Energies=          -2501.923389
 Sum of electronic and thermal Energies=             -2501.910252
 Sum of electronic and thermal Enthalpies=           -2501.909308
 Sum of electronic and thermal Free Energies=        -2501.966841
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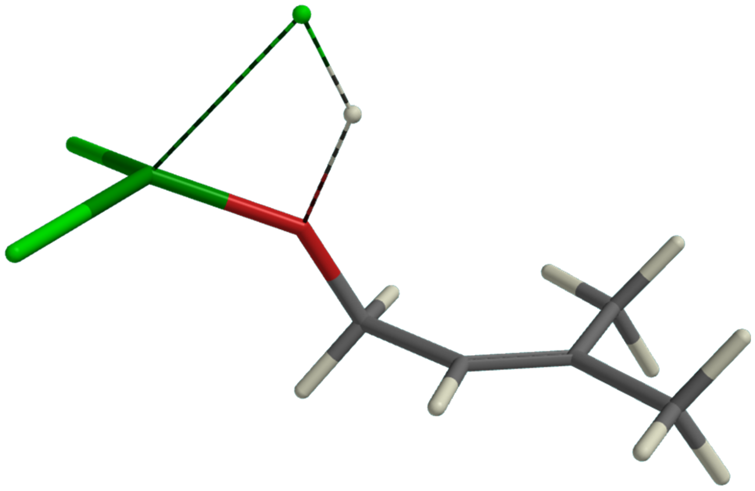
3.4.2. Structure, Cartesian Coordinates and Energies of TS$_{\mathrm{I}\rightarrow\mathrm{VII}}$[8]



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Charge = 0 Multiplicity = 2

6	2.457470000	0.061691000	-0.833444000
6	3.691622000	0.146177000	-0.303380000
1	2.237773000	-0.776179000	-1.494907000
6	1.309123000	1.002435000	-0.624840000
1	1.584828000	1.880976000	-0.035353000
1	0.921439000	1.352996000	-1.590470000
8	0.234010000	0.335756000	0.065937000
1	0.304197000	-0.909705000	1.214817000
22	-1.595460000	0.088683000	-0.009832000
17	-2.512128000	-1.282341000	-1.522993000
17	-0.580467000	-1.707230000	1.837553000
17	-2.673070000	2.013226000	0.375210000
6	4.165587000	1.234193000	0.629486000
1	4.573311000	0.792923000	1.547671000
1	4.983007000	1.803341000	0.168261000
1	3.384386000	1.940782000	0.914636000
6	4.739862000	-0.888714000	-0.636830000
1	5.614452000	-0.420022000	-1.106492000
1	5.101349000	-1.383242000	0.274121000
1	4.357615000	-1.655753000	-1.315538000

Zero-point correction= 0.139788 (Hartree/Particle)
Thermal correction to Energy= 0.151688
Thermal correction to Enthalpy= 0.152633
Thermal correction to Gibbs Free Energy= 0.097639
Sum of electronic and zero-point Energies= -2501.877380
Sum of electronic and thermal Energies= -2501.865479
Sum of electronic and thermal Enthalpies= -2501.864535
Sum of electronic and thermal Free Energies= -2501.919529

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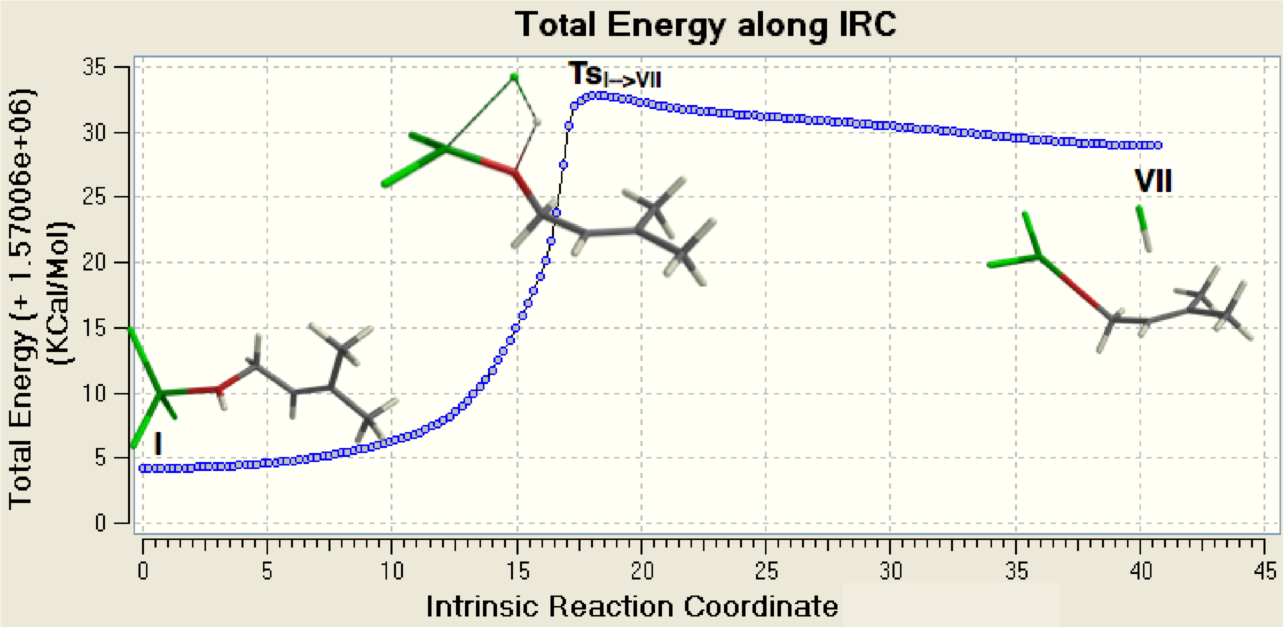
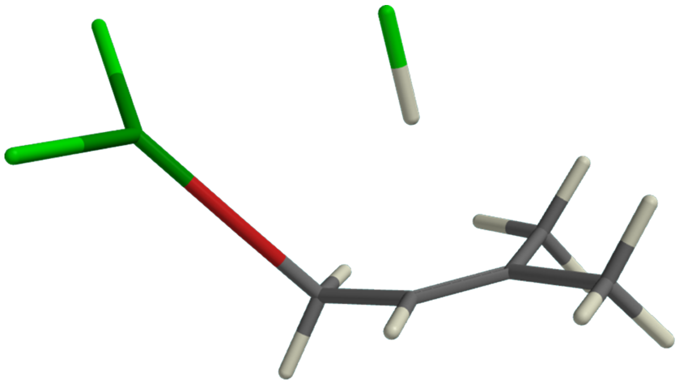
[8] **TS$_{\mathrm{I}\rightarrow\mathrm{VII}}$**: theoretical intermediate for direct elimination of HCl from complex **I**

3.4.3. Plot of IRC (**I** → **VII**)



3.4.4. Structure, Cartesian Coordinates and Energies of **$TiCl_2RO$ + HCl (VII)**[9]



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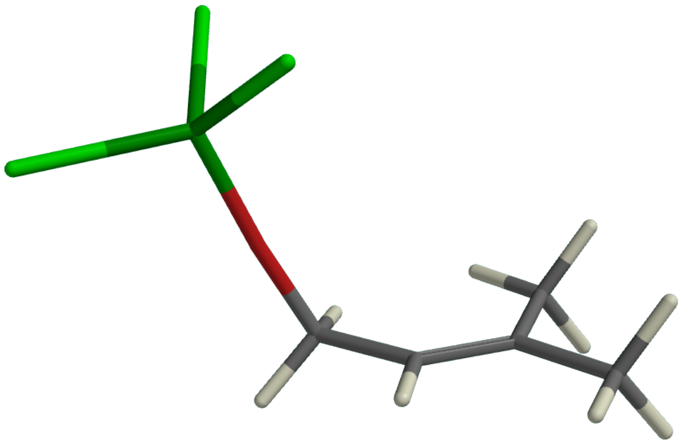
--------------------------------------------------------------

# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // #opt freq b3lyp/6-31+g(d,p)
geom=connectivity
Charge = 0 Multiplicity = 2
-------------------------------------------------------------
6      2.191716000    -0.223296000    -1.095292000
6      3.313907000     0.092884000    -0.415210000
1      2.020251000    -1.269563000    -1.348376000
6      1.136290000     0.716656000    -1.608565000
1      1.369915000     1.764747000    -1.401700000
1      1.028027000     0.602325000    -2.695021000
8     -0.127655000     0.421066000    -1.024305000
1      1.448867000    -0.573377000     1.085532000
22    -1.702210000     0.113363000    -0.289590000
17    -2.717013000    -1.850017000    -0.677299000
17     0.765534000    -0.824409000     2.166724000
17    -2.787679000     1.808388000     0.700465000
6      3.713024000     1.488061000    -0.000940000
1      3.932531000     1.514824000     1.073247000
1      4.635775000     1.784419000    -0.515712000
1      2.954034000     2.243759000    -0.208815000
6      4.301118000    -0.982553000    -0.027625000
1      5.280387000    -0.784417000    -0.481602000
1      4.456528000    -0.996792000     1.058519000
1      3.972903000    -1.976308000    -0.342985000
--------------------------------------------------------------
Zero-point correction=                     0.140725 (Hartree/Particle)
 Thermal correction to Energy=                  0.154489
 Thermal correction to Enthalpy=                0.155433
 Thermal correction to Gibbs Free Energy=       0.095294
 Sum of electronic and zero-point Energies=        -2501.887211
 Sum of electronic and thermal Energies=           -2501.873447
 Sum of electronic and thermal Enthalpies=         -2501.872503
 Sum of electronic and thermal Free Energies=       -2501.932641
```

---

[9] **VII**: theoretical intermediate that represents the product coming from direct elimination of HCl from complex **I**

3.4.5. Structure, Cartesian Coordinates and Energies of **$TiCl_3OR$ (VIII)**[10]



```
---------------------------------------------------------------
# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity //# opt freq b3lyp/6-31+g(d,p)
geom=connectivity
Charge = 0 Multiplicity = 1
---------------------------------------------------------------
```

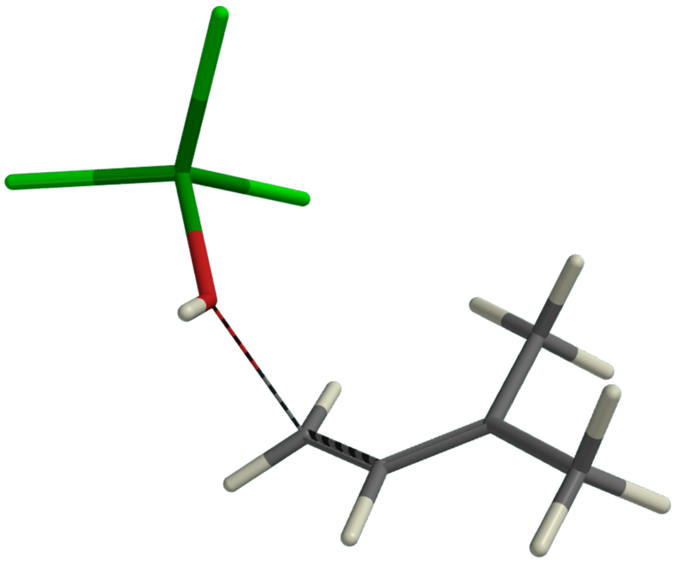
6	-0.225123000	-0.414531000	1.154208000
6	1.092681000	-0.420678000	0.890625000
1	1.503041000	0.375525000	0.272495000
6	2.096306000	-1.421412000	1.365830000
1	1.643418000	-2.293324000	1.843110000
1	2.733786000	-1.768285000	0.544431000
8	2.987317000	-0.835867000	2.332977000
22	4.010065300	-0.012687990	3.432631750
17	5.512652540	-1.434597240	4.214581190
17	2.773796260	0.779851630	5.086385810
17	5.015457740	1.648636610	2.377821170
6	-0.949337000	-1.431533000	1.999334000
1	-1.710990000	-1.950471000	1.404170000
1	-0.297369000	-2.185059000	2.443658000
1	-1.482178000	-0.928758000	2.815262000
6	-1.108802000	0.664614000	0.579972000
1	-0.776094970	1.657064560	0.909392840
1	-1.054767190	0.664913350	-0.515695460
1	-2.154060240	0.538333480	0.871410220

```
---------------------------------------------------------------
 Zero-point correction=                           0.134668 (Hartree/Particle)
 Thermal correction to Energy=                    0.145900
 Thermal correction to Enthalpy=                  0.146844
 Thermal correction to Gibbs Free Energy=         0.094998
 Sum of electronic and zero-point Energies=       -2501.350152
 Sum of electronic and thermal Energies=          -2501.338920
 Sum of electronic and thermal Enthalpies=        -2501.337976
 Sum of electronic and thermal Free Energies=     -2501.389822
```

---

[10] **VIII**: theoretical intermediate that represents the product coming from elimination of H-atom from complex **I**.

3.4.6. Structure, Cartesian Coordinates and Energies of **r05**

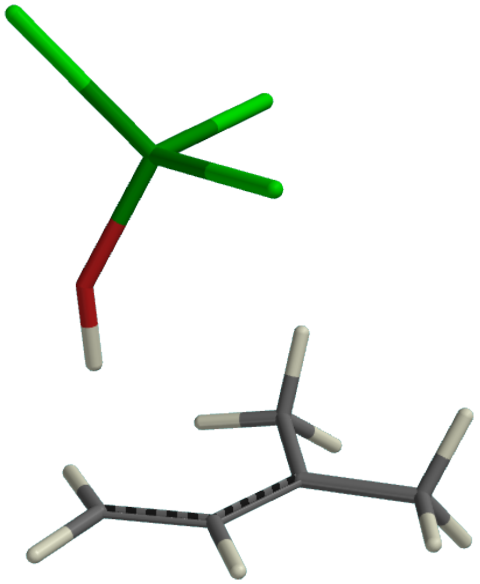


# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt=(calcall,ts) b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 2

6	-2.850039000	-1.110335000	-0.659401000
6	-3.549326000	-0.046568000	-0.135378000
1	-3.232162000	-1.556966000	-1.576048000
6	-1.671090000	-1.671478000	-0.115890000
1	-1.336279000	-1.422377000	0.882813000
1	-1.305906000	-2.611457000	-0.511610000
8	-0.062451000	-0.657180000	-0.896668000
1	-0.315426000	-0.507436000	-1.817703000
22	1.452060000	0.069786000	-0.062326000
17	3.214743000	-1.205450000	-0.583428000
17	1.594083000	2.210688000	-0.712584000
17	0.808947000	-0.089611000	2.110487000
6	-3.148604000	0.696879000	1.104140000
1	-2.182449000	0.398020000	1.510566000
1	-3.108906000	1.773639000	0.896385000
1	-3.911268000	0.563301000	1.883402000
6	-4.804925000	0.431558000	-0.804791000
1	-5.649007000	0.407852000	-0.102801000
1	-4.697432000	1.478900000	-1.117744000
1	-5.065114000	-0.167315000	-1.680903000

Zero-point correction= 0.141474 (Hartree/Particle)
Thermal correction to Energy= 0.154850
Thermal correction to Enthalpy= 0.155794
Thermal correction to Gibbs Free Energy= 0.097672
Sum of electronic and zero-point Energies= -2501.903905
Sum of electronic and thermal Energies= -2501.890528
Sum of electronic and thermal Enthalpies= -2501.889584
Sum of electronic and thermal Free Energies= -2501.947706

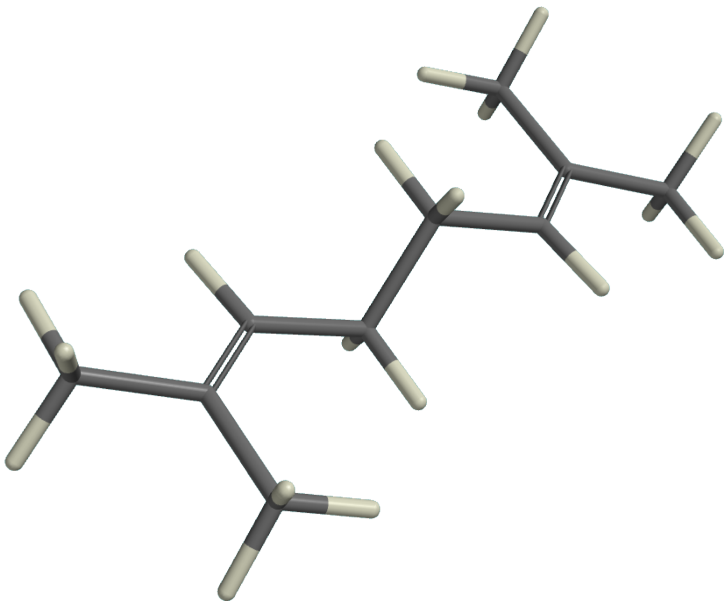
3.4.7. Structure, Cartesian Coordinates and Energies of **R + TiCl$_3$OH**



```
---------------------------------------------------------------

#  freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt freq b3lyp/6-
31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 2
--------------------------------------------------------------
6     -3.040493000     0.958280000     0.837126000
6     -3.413546000    -0.111389000     0.012854000
1     -3.045676000     0.757200000     1.908599000
6     -2.646796000     2.233610000     0.449233000
1     -2.655367000     2.557403000    -0.586971000
1     -2.441237000     2.993203000     1.196766000
8      0.244675000     1.333926000     0.241304000
1     -0.704930000     1.574721000     0.361940000
22     1.409878000     0.067209000     0.012870000
17     3.388264000     0.951864000    -0.406873000
17     1.491351000    -1.178648000     1.834355000
17     0.756426000    -1.200365000    -1.677628000
6     -3.446100000    -0.025492000    -1.485396000
1     -3.378295000     0.997412000    -1.861004000
1     -2.613953000    -0.597482000    -1.920831000
1     -4.369020000    -0.470711000    -1.877600000
6     -3.777619000    -1.438967000     0.611445000
1     -4.805429000    -1.721848000     0.343434000
1     -3.129309000    -2.236213000     0.221183000
1     -3.696853000    -1.438398000     1.701832000
--------------------------------------------------------------
Zero-point correction=                         0.139370 (Hartree/Particle)
 Thermal correction to Energy=                  0.152311
 Thermal correction to Enthalpy=                0.153255
 Thermal correction to Gibbs Free Energy=       0.096886
 Sum of electronic and zero-point Energies=        -2501,921823
 Sum of electronic and thermal Energies=          -2501.908883
 Sum of electronic and thermal Enthalpies=         -2501.907939
 Sum of electronic and thermal Free Energies=        -2501.964308
--------------------------------------------------------------
```

3.4.8. Structure, Cartesian Coordinates and Energies of **R-R**[11]



\# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt freq b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 1

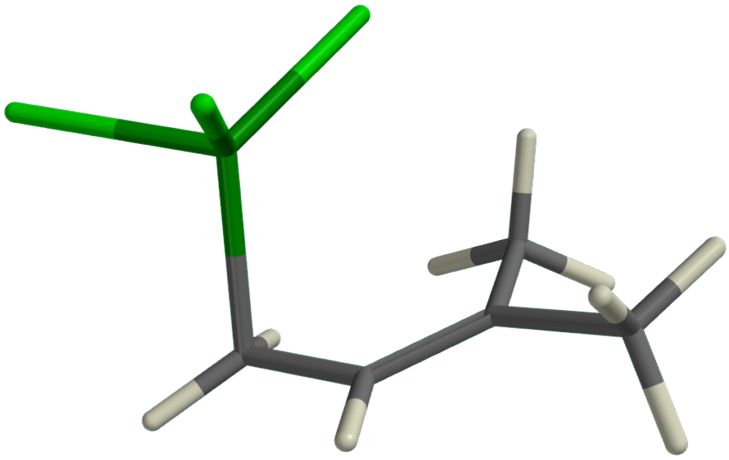
6	-0.060805000	-0.006126000	1.368362000
6	-0.028470000	1.368242000	1.997161000
1	0.789973000	1.449612000	2.725336000
1	-0.957051000	1.571021000	2.548064000
1	0.101655000	2.156198000	1.249578000
6	-0.240975000	-1.135140000	2.355340000
1	0.559610000	-1.119183000	3.106862000
1	-0.243304000	-2.122072000	1.889133000
1	-1.185069000	-1.020141000	2.904773000
6	0.058491000	-0.157942000	0.037443000
1	0.186848000	0.751324000	-0.553549000
6	0.052816000	-1.427505000	-0.771698000
1	-0.750353000	-1.375745000	-1.520667000
1	-0.169271000	-2.299288000	-0.147221000
6	1.390623000	-1.666226000	-1.518410000
1	2.193792000	-1.717987000	-0.769441000
1	1.612710000	-0.794444000	-2.142887000
6	1.384947000	-2.935789000	-2.327551000
1	1.256591000	-3.845055000	-1.736559000
6	1.504244000	-3.087605000	-3.658470000
6	1.684414000	-1.958592000	-4.645448000
1	2.628507000	-2.073591000	-5.194881000
1	1.686743000	-0.971660000	-4.179241000
1	0.883828000	-1.974548000	-5.396970000
6	1.471908000	-4.461974000	-4.287269000
1	2.400490000	-4.664753000	-4.838172000

---

[11] Homocoupling product R–R (R = dimethylallyl)

```
1       0.653466000     -4.543343000     -5.015444000
1       1.341783000     -5.249930000     -3.539686000
---------------------------------------------------------------------
Zero-point correction=                           0.253410 (Hartree/Particle)
 Thermal correction to Energy=                    0.266706
 Thermal correction to Enthalpy=                  0.267650
 Thermal correction to Gibbs Free Energy=         0.212826
 Sum of electronic and zero-point Energies=           -391.677171
 Sum of electronic and thermal Energies=              -391.663875
 Sum of electronic and thermal Enthalpies=            -391.662931
 Sum of electronic and thermal Free Energies=         -391.717755
---------------------------------------------------------------------
```

3.4.9. Structure, Cartesian Coordinates and Energies of **$TiCl_3R$**

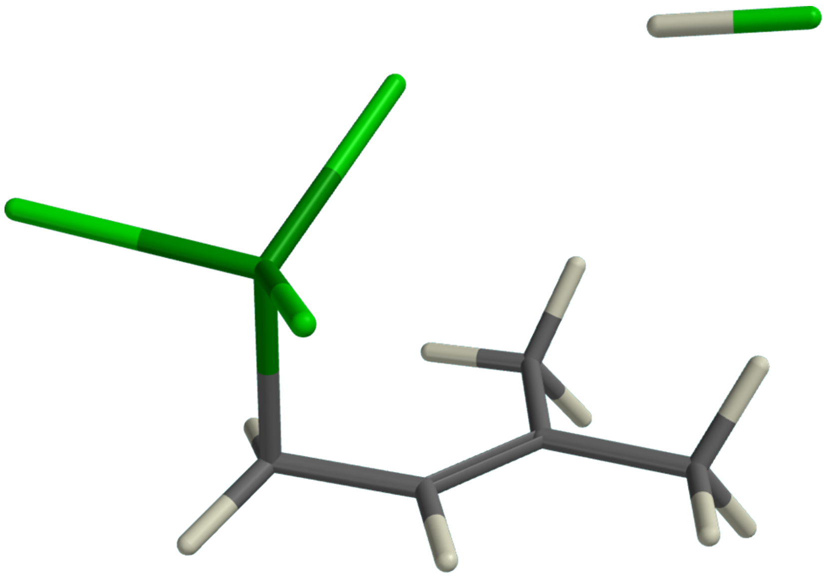


# opt freq b3lyp/6-31+g(d,p) geom=connectivity // # freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity
Charge = 0 Multiplicity = 1

1	-0.246270000	0.724528000	2.153248000
6	-0.214612000	-0.301298000	1.781229000
1	-0.471189000	-1.022432000	2.561498000
6	0.920769000	-0.621365000	0.903543000
1	1.345310000	0.219851000	0.35883600
6	1.472978000	-1.845423000	0.652165000
22	-1.522028000	-0.532088000	0.202137000
17	-1.009250000	0.880008000	-1.434157000
17	-3.371111000	0.204631000	1.164143000
17	-1.885176000	-2.657724000	-0.347007000
6	1.091550000	-3.113165000	1.361457000
1	1.988507000	-3.576742000	1.791419000
1	0.666327000	-3.837595000	0.656059000
1	0.366786000	-2.964214000	2.163129000
6	2.575370000	-1.984744000	-0.363214000
1	3.489993000	-2.366367000	0.109127000
1	2.808377000	-1.036348000	-0.853407000
1	2.296560000	-2.713474000	-1.135518000

Zero-point correction= 0.128668 (Hartree/Particle)
Thermal correction to Energy= 0.141457
Thermal correction to Enthalpy= 0.142401
Thermal correction to Gibbs Free Energy= 0.087193
Sum of electronic and zero-point Energies= -2426.083357
Sum of electronic and thermal Energies= -2426.070569
Sum of electronic and thermal Enthalpies= -2426.069624
Sum of electronic and thermal Free Energies= -2426.124833

3.4.10. -Structure, Cartesian Coordinates and Energies of **TiCl$_3$R +HCl**



----

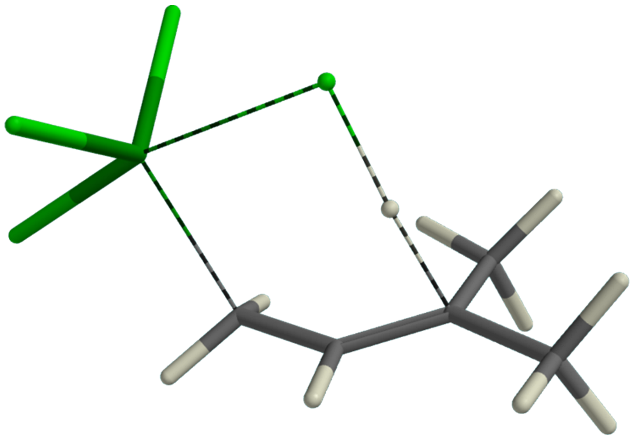
freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt=(calcall,ts) b3lyp/6-31+g(d,p) geom=connectivity

Charge = 0 Multiplicity = 1

1	2.214875000	2.250854000	0.469664000
6	1.350293000	1.890838000	-0.090559000
1	1.396517000	2.184187000	-1.142458000
6	0.055640000	2.000159000	0.595219000
1	0.096887000	2.004173000	1.682886000
22	1.207763000	-0.161235000	0.020085000
6	-1.192299000	2.055485000	0.036772000
6	-2.414565000	2.074952000	0.913555000
1	-2.990747000	2.994204000	0.745764000
1	-2.163622000	2.011317000	1.974994000
1	-3.080713000	1.239055000	0.665100000
6	-1.459557000	2.158755000	-1.437327000
1	-0.555573000	2.205560000	-2.045854000
1	-2.054180000	3.059673000	-1.635298000
1	-2.056243000	1.306140000	-1.782733000
1	-2.446508000	-1.750888000	-0.370558000
17	-0.278675000	-1.093917000	-1.388199000
17	3.201238000	-0.677893000	-0.779022000
17	1.147345000	-0.805127000	2.137741000
17	-3.656294000	-1.837077000	0.081872000

Zero-point correction= 0.136673 (Hartree/Particle)
Thermal correction to Energy= 0.152980
Thermal correction to Enthalpy= 0.153924
Thermal correction to Gibbs Free Energy= 0.089049
Sum of electronic and zero-point Energies= -2886.884816
Sum of electronic and thermal Energies= -2886.868509
Sum of electronic and thermal Enthalpies= -2886.867565
Sum of electronic and thermal Free Energies= -2886.932440

3.4.11. Structure, Cartesian Coordinates and Energies of **b10**

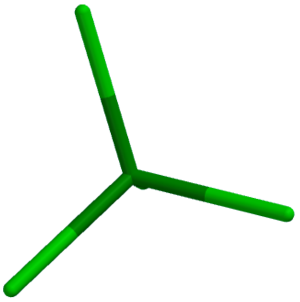


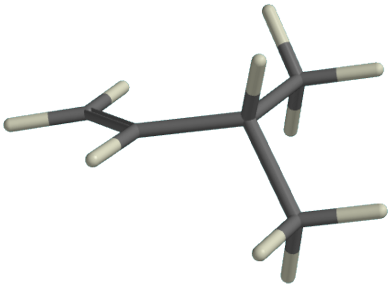
\# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt=(calcall,ts) b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 1

1	0.584330000	-1.978754000	-1.020346000
6	-0.082395000	-1.483716000	-0.312592000
1	0.009768000	-1.942893000	0.677486000
6	-1.429640000	-1.384124000	-0.834323000
1	-1.505882000	-1.300420000	-1.919619000
22	1.134707000	0.347497000	0.036420000
6	-2.608590000	-1.195923000	-0.137344000
6	-3.926374000	-1.099853000	-0.878487000
1	-4.508413000	-2.018072000	-0.731479000
1	-3.784310000	-0.955767000	-1.953183000
1	-4.533714000	-0.271481000	-0.496989000
6	-2.716236000	-1.388498000	1.361698000
1	-1.759222000	-1.290323000	1.876696000
1	-3.116224000	-2.388310000	1.572638000
1	-3.408709000	-0.661257000	1.797318000
1	-1.944210000	0.143586000	-0.218947000
17	1.416683000	1.212474000	2.062946000
17	2.920019000	-0.999932000	0.075333000
17	1.647346000	1.568098000	-1.730591000
17	-1.189316000	1.477337000	0.082831000

Zero-point correction= 0.134990 (Hartree/Particle)
Thermal correction to Energy= 0.148555
Thermal correction to Enthalpy= 0.149499
Thermal correction to Gibbs Free Energy= 0.093651
Sum of electronic and zero-point Energies= -2886.864292
Sum of electronic and thermal Energies= -2886.850726
Sum of electronic and thermal Enthalpies= -2886.849782
Sum of electronic and thermal Free Energies= -2886.905631

3.4.12. -Structure, Cartesian Coordinates and Energies of **2 R–H**[12] **+ Cl$_4$Ti**





\# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt freq b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 1

1	2.624878000	2.808374000	-0.339584000
6	3.040458000	1.921133000	0.129487000
1	3.244044000	1.986658000	1.194440000
6	3.283046000	0.814890000	-0.581568000
1	3.052770000	0.828187000	-1.648649000
22	-1.748819000	-0.055631000	-0.008336000
6	3.866216000	-0.488930000	-0.084012000
6	5.114230000	-0.859059000	-0.912615000
1	5.917847000	-0.131993000	-0.747764000
1	4.891960000	-0.875179000	-1.985441000
1	5.488443000	-1.849811000	-0.631697000
6	4.173742000	-0.508493000	1.418040000
1	3.281662000	-0.298447000	2.017174000
1	4.937784000	0.234527000	1.675564000
1	4.553083000	-1.491725000	1.716024000
1	3.109480000	-1.265362000	-0.282087000
17	-3.815703000	-0.753733000	0.026968000
17	-1.365585000	1.135506000	1.776660000
17	-1.435914000	1.162396000	-1.789793000
17	-0.411861000	-1.779381000	-0.049164000

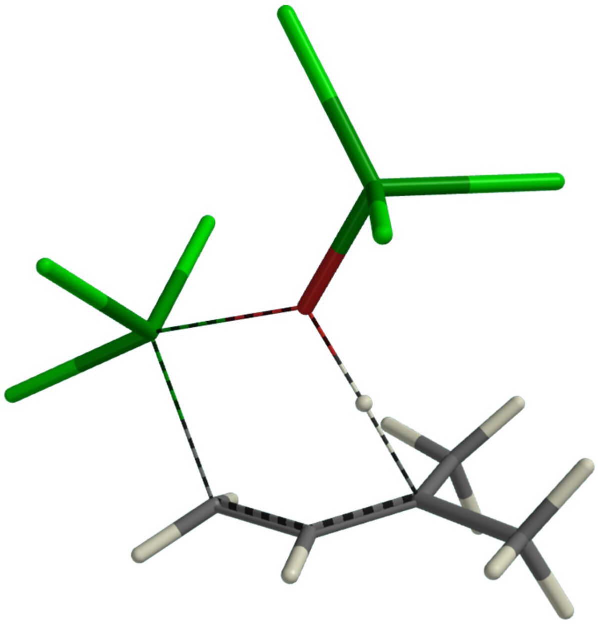
Zero-point correction= 0.141879 (Hartree/Particle)
Thermal correction to Energy= 0.155573
Thermal correction to Enthalpy= 0.156518

---

[12] Reduction product R–H (R = dimethylallyl)

```
 Thermal correction to Gibbs Free Energy=         0.096745
 Sum of electronic and zero-point Energies=          -2886.917515
 Sum of electronic and thermal Energies=             -2886.903820
 Sum of electronic and thermal Enthalpies=           -2886.902876
 Sum of electronic and thermal Free Energies=        -2886.962649
------------------------------------------------------------------
```

3.4.13. Structure, Cartesian Coordinates and Energies of **b09**



----

freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt=(calcall,ts) b3lyp/6-31+g(d,p) geom=connectivity

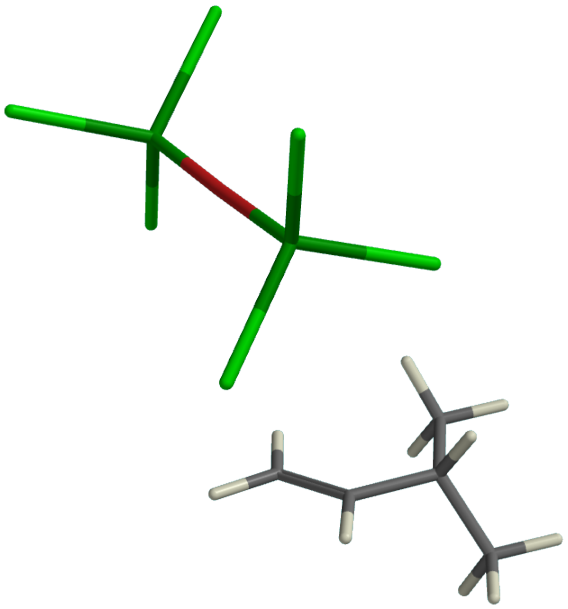
Charge = 0 Multiplicity = 1

1	-2.678255000	1.945361000	-1.391796000
6	-1.939001000	1.970671000	-0.592587000
1	-2.371390000	2.344048000	0.340292000
6	-0.684030000	2.543768000	-0.991973000
1	-0.453567000	2.490014000	-2.057605000
22	-1.813284000	-0.196254000	-0.033197000
6	0.371561000	2.932616000	-0.171062000
6	1.633208000	3.507091000	-0.788092000
1	1.630480000	4.599814000	-0.691178000
1	1.721590000	3.261319000	-1.850165000
1	2.526743000	3.140301000	-0.273338000
6	0.187327000	3.203526000	1.312034000
1	-0.619973000	2.620436000	1.759179000
1	-0.038343000	4.266653000	1.462694000
1	1.106573000	2.980041000	1.860421000
1	0.400184000	1.532546000	-0.222495000
8	0.243167000	0.247258000	-0.002017000
22	1.744482000	-0.699526000	0.034126000
17	1.463805000	-2.750506000	0.758850000
17	2.607412000	-0.676861000	-1.996594000
17	3.141594000	0.374070000	1.370003000
17	-1.670954000	-0.711920000	2.125008000
17	-4.050253000	-0.176289000	-0.161503000
17	-1.436906000	-1.728932000	-1.598718000

Zero-point correction= 0.143658 (Hartree/Particle)
Thermal correction to Energy= 0.163652

```
 Thermal correction to Enthalpy=                 0.164596
 Thermal correction to Gibbs Free Energy=        0.091822
 Sum of electronic and zero-point Energies=         -4732.176472
 Sum of electronic and thermal Energies=            -4732.156478
 Sum of electronic and thermal Enthalpies=          -4732.155534
 Sum of electronic and thermal Free Energies=       -4732.228308
----------------------------------------------------------------
```

3.4.14. Structure, Cartesian Coordinates and Energies of **R–H**[13] + $(TiCl_3)_2O$



\# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt freq b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 1

1	2.967084000	-1.714671000	2.483912000
6	3.407561000	-1.769534000	1.492483000
1	3.258209000	-2.696813000	0.946999000
6	4.096012000	-0.740833000	0.986419000
1	4.203994000	0.156871000	1.598174000
22	-2.078707000	-1.281958000	-0.030874000
6	4.777607000	-0.664533000	-0.361596000
6	6.268401000	-0.310091000	-0.179558000
1	6.798151000	-1.118567000	0.337486000
1	6.393013000	0.603928000	0.411745000
1	6.752371000	-0.151662000	-1.149723000
6	4.608981000	-1.920782000	-1.224378000
1	3.553544000	-2.151476000	-1.402636000
1	5.070661000	-2.793607000	-0.747737000
1	5.090065000	-1.781088000	-2.198267000
1	4.312617000	0.177438000	-0.899545000
8	-1.168006000	0.257071000	-0.008264000
22	-0.331182000	1.837563000	-0.009029000
17	-1.780322000	3.401156000	-0.509127000
17	0.500368000	2.217786000	1.979849000
17	1.265889000	1.812514000	-1.507450000
17	-2.922289000	-1.579265000	-2.029698000
17	-0.727115000	-2.932102000	0.457145000
17	-3.688851000	-1.177477000	1.449478000

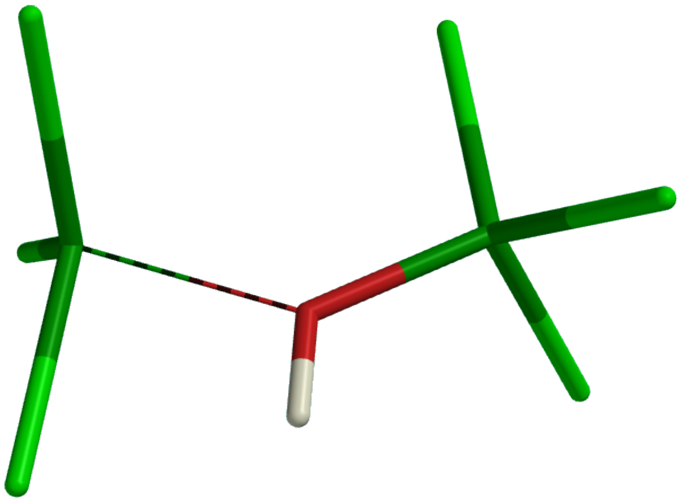
Zero-point correction=   0.148136 (Hartree/Particle)

---

[13] Reduction product R–H (R = dimethylallyl)

```
 Thermal correction to Energy=                    0.166138
 Thermal correction to Enthalpy=                  0.167082
 Thermal correction to Gibbs Free Energy=         0.096390
 Sum of electronic and zero-point Energies=          -4732.233611
 Sum of electronic and thermal Energies=             -4732.215609
 Sum of electronic and thermal Enthalpies=           -4732.214664
 Sum of electronic and thermal Free Energies=        -4732.285357
------------------------------------------------------------------
```

3.4.15. Structure, Cartesian Coordinates and Energies of **$TiCl_3)_2OH$**



```
--------------------------------------------------------------
```

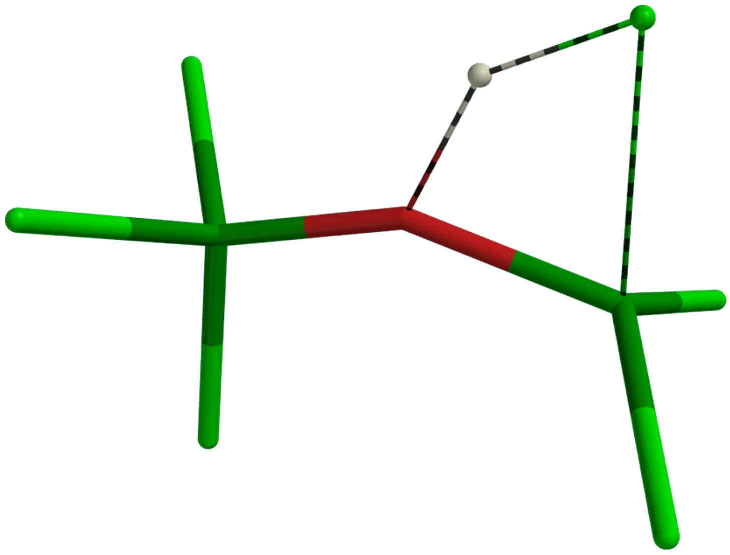
# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt freq b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 2

```
--------------------------------------------------------------
```

8	-0.093698000	0.749399000	0.000062000
22	-1.755566000	-0.074379000	-0.000012000
17	-2.844248000	0.575972000	1.766304000
17	-2.844332000	0.576475000	-1.766090000
17	-1.497782000	-2.229019000	-0.000323000
22	1.927925000	0.125958000	0.000012000
17	2.319316000	-0.888584000	1.947556000
17	2.319363000	-0.888166000	-1.947740000
17	2.353659000	2.390154000	0.000258000
1	0.016141000	1.726551000	0.000165000

```
--------------------------------------------------------------
 Zero-point correction=                     0.021807 (Hartree/Particle)
 Thermal correction to Energy=                  0.034356
 Thermal correction to Enthalpy=                0.035301
 Thermal correction to Gibbs Free Energy=      -0.022212
 Sum of electronic and zero-point Energies=       -4536.358491
 Sum of electronic and thermal Energies=          -4536.345941
 Sum of electronic and thermal Enthalpies=        -4536.344997
 Sum of electronic and thermal Free Energies=      -4536.402509
--------------------------------------------------------------
```

3.4.16. Structure, Cartesian Coordinates and Energies of **b13**

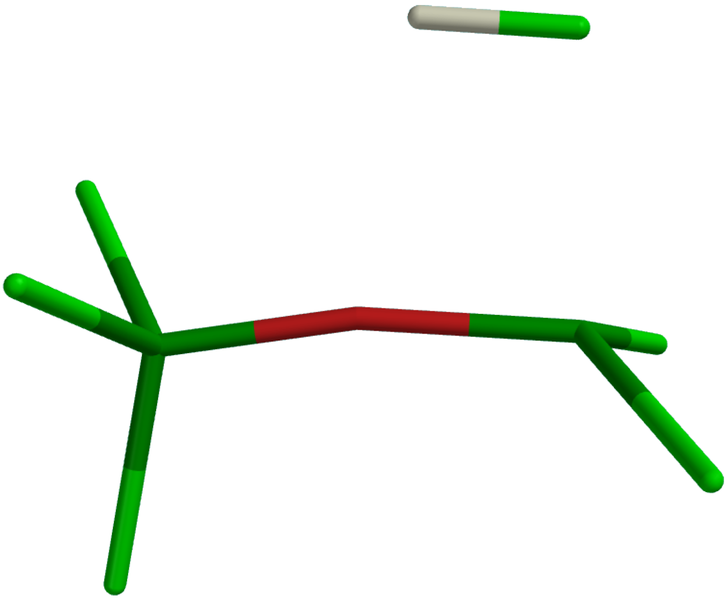


\# freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt=(calcall,ts) b3lyp/6-31+g(d,p) geom=connectivity
Charge = 0 Multiplicity = 2

8	-0.031633000	0.406872000	0.000010000
22	-1.730056000	-0.085225000	-0.000008000
17	-2.692363000	0.733335000	1.801295000
17	-2.692402000	0.733593000	-1.801172000
17	-1.809411000	-2.282178000	-0.000163000
22	1.894085000	-0.055044000	-0.000003000
17	2.607389000	-0.882097000	1.924642000
17	2.607417000	-0.881897000	-1.924723000
17	1.751390000	2.463640000	0.000124000
1	0.520109000	1.796193000	0.000082000

Zero-point correction= 0.016153 (Hartree/Particle)
Thermal correction to Energy= 0.026044
Thermal correction to Enthalpy= 0.026988
Thermal correction to Gibbs Free Energy= -0.023978
Sum of electronic and zero-point Energies= -4536.342098
Sum of electronic and thermal Energies= -4536.332207
Sum of electronic and thermal Enthalpies= -4536.331263
Sum of electronic and thermal Free Energies= -4536.382229

3.4.17. Structure, Cartesian Coordinates and Energies of $\mathbf{Ti_2Cl_5O}$



```
#  freq b3lyp/6-31+g(d,p) scrf=(smd,solvent=thf) geom=connectivity // # opt freq b3lyp/6-31+g(d,p) geom=connectivity
```

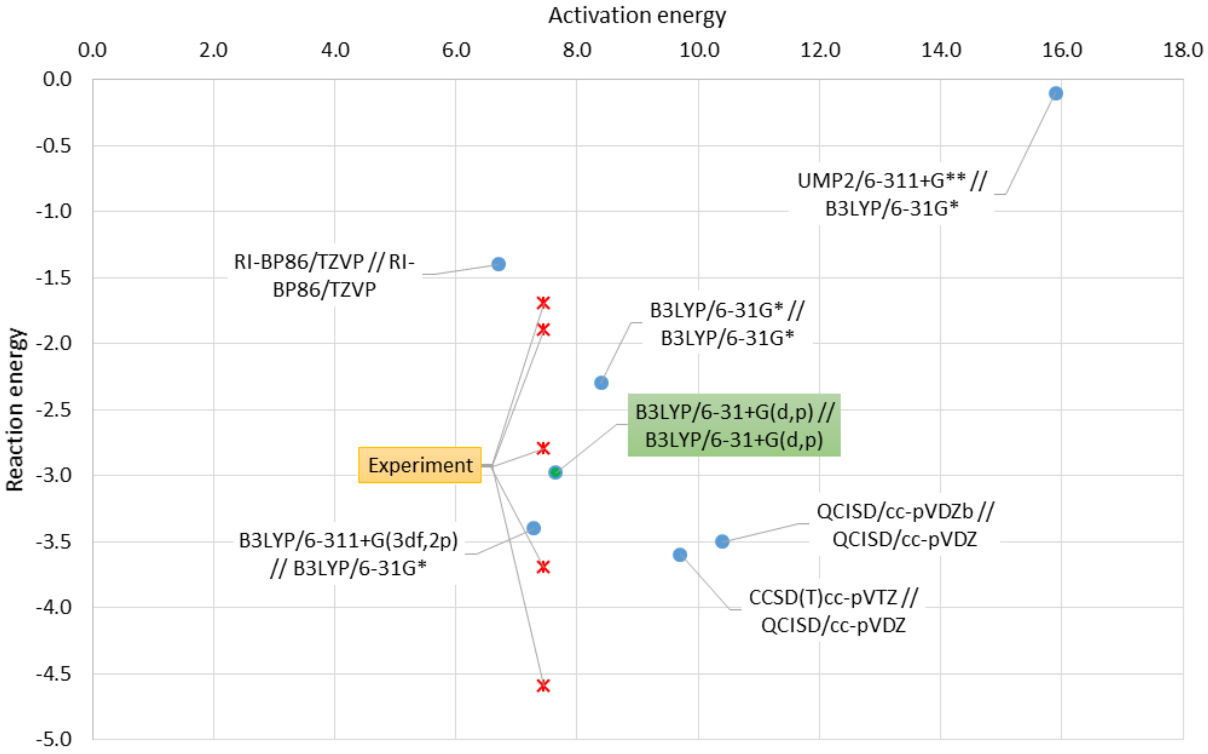
Charge = 0 Multiplicity = 2

8	-0.011439000	0.038072000	0.000158000
22	-1.736373000	-0.138381000	0.000119000
17	-2.503262000	0.889435000	1.808042000
17	-2.503144000	0.891560000	-1.806689000
17	-2.260517000	-2.284818000	-0.001115000
22	1.887294000	0.007930000	0.000121000
17	2.783054000	-0.607132000	1.934533000
17	2.783370000	-0.607349000	-1.934066000
17	1.709307000	2.582641000	-0.000288000
1	0.412254000	2.633187000	-0.000746000

Zero-point correction= 0.018011 (Hartree/Particle)
Thermal correction to Energy= 0.029923
Thermal correction to Enthalpy= 0.030867
Thermal correction to Gibbs Free Energy= -0.025537
Sum of electronic and zero-point Energies= -4536,348686
Sum of electronic and thermal Energies= -4536.336774
Sum of electronic and thermal Enthalpies= -4536.335830
Sum of electronic and thermal Free Energies= -4536.392234

3.5. - COMPARATIVE STUDY ON THE PERFORMANCE OF SEVERAL COMPUTATION MODELS

We performed all reaction energy calculations with DFT using the B3LYP/6-31+G(d,p) model. Friedrich et al.[14] carried out a comparative study on the performance of several models for this type of reactions. We have plotted below some of their results for the reaction and activation energies for the ring opening of the cyclopropylcarbinyl radical, as well as experimental values (there is a large scatter in the reaction energy measurements) and the result that we obtain with B3LYP/6-31+G(d,p): our DFT model chemistry yields predictions in excellent agreement with the experimental values, even closer than the MP2 and CC methods tested for these reactions.



Another comparative study of activation energies of 12 organic elementary gas-phase reactions (six of which had a radical species as a reactant) found the following average and maximum absolute errors in calculated barrier heights in kcal/mol: BLYP/6-31G* (5.9, 21.9), MP2/6-31G* (9.9, 28.8).[15] More recently, 205 combinations of methods and basis sets were tested using a database of 24 reaction barrier heights.[16] The database included four reaction sets (chosen to be statistically representative of a still larger experimental database): heavy-atom transfer, nucleophilic substitution, unimolecular and association reactions, and hydrogen-transfer reactions. Among their results we

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[14] J. Friedrich, M. Dolg, A. Gansäuer, D.Geich-Gimbel, T. Lauterbach, *J. Am. Chem. Soc.*, 2005, **127**, 7071-7077.

[15] J. Baker, M. Muir, J. Andzelm, *J. Chem. Phys.,* 1995, **102**, 2063-2079.

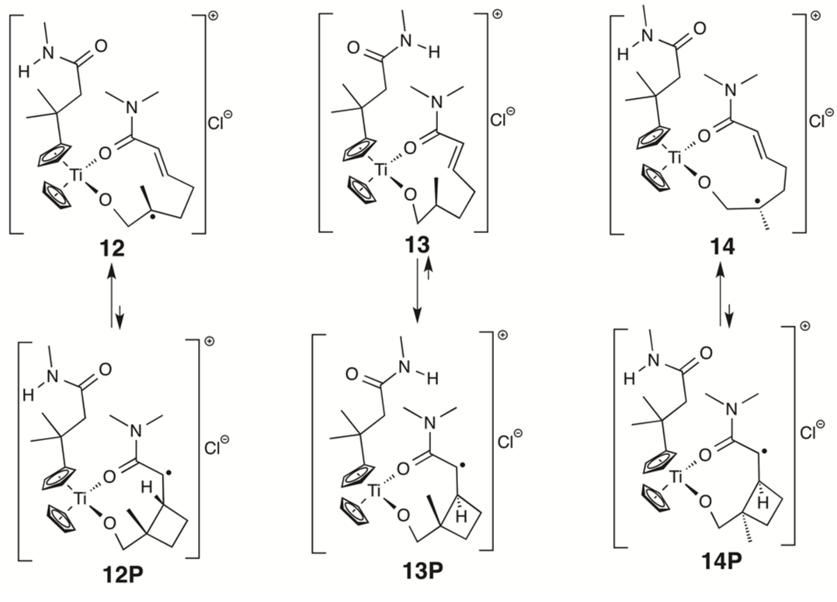
[16] J. Zheng, Y. Zhao, D.G. Truhlar, *J. Chem. Theory Comput*., 2007, **3**, 569-582.

highlight the following three (first number is the maximum absolute error in kcal/mol, second number is relative computation time): G3X (0.6, 250), B3LYP/6-31+G(d,p) (4.9, 1.4), MP2/6-31+G(d,p) (6.3, 1.0). In summary, B3LYP has proven to yield fairly reliable predictions in activation energy calculations for different reaction types, even better than MP2.

As a further test within our reaction set, we have also calculated with MP2/6-31+G(d,p) the reaction barriers for r10 and r13 and the results are: b10 = 12.5, b13 = 11.4, b13r = 7.1. The first two values are close to those given in Table 3 for B3LYP/6-31+G(d,p) which are b10 = 12.9, b13 = 10.3. As for b13r, based on the previous discussion, the B3LYP value (1.4) should be more reliable.

3.6. - COMPARATIVE BEHAVIOUR OF $TiCl_3$ - Cp_2TiCl

To facilitate the study of the high number of reactions involved (listed in Table 3) with this accurate method we considered the $TiCl_4/TiCl_3$ system instead of Cp_2TiCl_2/Cp_2TiCl. This reduces the computational cost as well as the structural complexity of some intermediates possessing two titanocene moieties. From the experimental point of view, it is well established that both systems have shown similar behaviour (Ref. 12 of the text), although $TiCl_3$ is less selective and yields more side products due to its higher reactivity. To confirm that this similarity is also true from the theoretical approach, we compared the results obtained with Cp_2TiCl for a similar radical system, carried out by Gansäuer et al. (Ref 13 of the text), and the predictions that we obtain with $TiCl_3$. In their work, geometry optimization of a templated radical resulted in three structures **12**, **13** and **14**. Of these, **12** and **14** lead to the formation of a *cis*- and **13** to a *trans*-cyclobutylcarbinyl radical. The forward reaction (cyclization) barrier is similar for all three but the **13P** product has a higher barrier for the reverse reaction (opening) than **12P** and **14P**, and therefore a longer life-time. This allows for the reduction of **13P** by a second equivalent of the titanocene leading to only *trans*-cyclobutane, exactly as observed experimentally. Replacing their Cp_2TiCl_2/Cp_2TiCl system for $TiCl_4/TiCl_3$ we obtain essentially the same reaction path and predictions: the forward barriers are similar for all three (although smaller than for the titanocene system, in agreement with the different reactivity) and the reverse barrier from **13P** is again much higher than from **12P** and **14P**, thus leading to only *trans*-cyclobutane.



The three structures (**12**, **13** and **14**) of the radical **9** and the *cis*- and *trans*- cyclobutylcarbinyl radicals (**12P**, **14P** and **13P)** on the reference 13 on the text.

The Cp-moieties contribute to the increased forward reaction barriers of the Cp_2TiCl_2/Cp_2TiCl system and therefore to its reduced reactivity. But, overall we can expect that the results from our theoretical study with the $TiCl_4$/$TiCl_3$ system are representative of what would have been obtained with Cp_2TiCl_2/Cp_2TiCl.