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Factors Controlling Reactivity in the Hydrogen Atom Transfer and Radical Addition Steps of a Radical Relay Cascade

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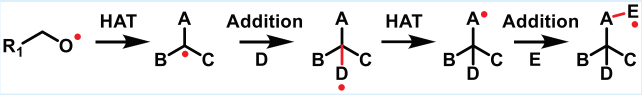
Supporting Information

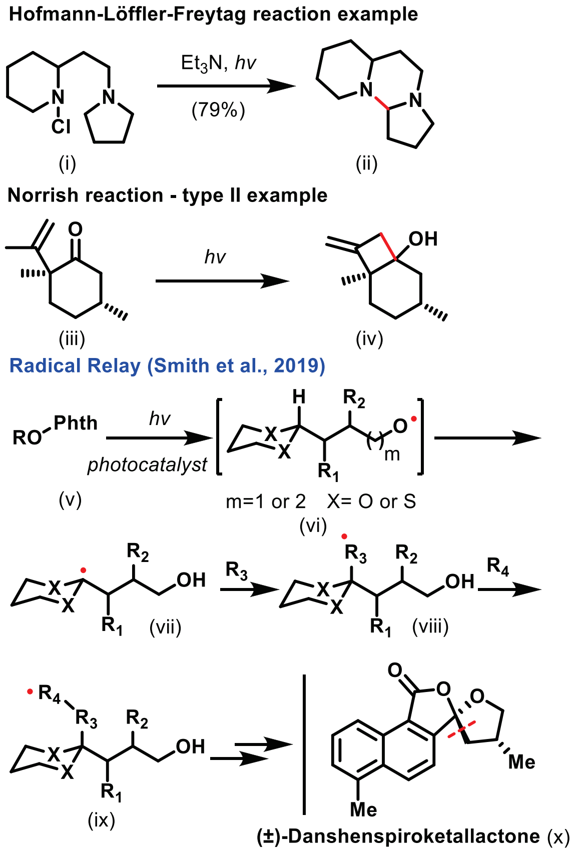
ABSTRACT: DFT exploration of 1,5- and 1,6-hydrogen atom transfers (HAT), radical addition, and relay to alkene is reported. The reactivity of 1,5- and 1,6-HAT are similar. We also explored reactions involving a multiple radical transferring process. Initially generated radicals undergo a multiple HAT process to form multiple bonds in a "relay" fashion, provided by exquisitely balanced rates.



The hydrogen atom transfer (HAT) reaction transfers a radical center from the original site to a distal position.[1] Although the newly generated radical specie is less reactive than the original one, a new bond can now be formed at the distal position, if the lifetime is sufficient for a subsequent addition reaction. One of the earliest examples of a HAT reaction is the Hofmann−Löffler−Freytag reaction,[2] in which the initial nitrogen based radical, generated via photolytic homolysis of the N−Cl bond such as in (i), undergoes an intramolecular HAT process to relay the radical to a carbon center (Scheme 1) that subsequently reacts with the amine generated to give (ii). In the Norrish Type II reaction,[3] a carbonyl such as in (iii) excited to an n−π* state undergoes rapid intramolecular HAT to abstract a γ-hydrogen to produce a 1,4-biradical as the primary photoproduct. The resulting 1,4-biradical then undergoes subsequent reactions of intramolecular radical recombination [Yang cyclization to generate (iv)] and/or β-cleavage (Norrish Type II).

The most common synthetic applications of HAT involve 1,5- and 1,6-HAT reactions, wherein the newly generated radical-bearing atoms are in a 1,5- and 1,6-relationship respectively with the original radical centers.[4] Smith et al. recently reported a new synthetic application of the 1,5- and 1,6-HAT process in which an initial alkoxy radical (vi) was generated from a *N*-alkoxyphthalimide (v) via photoredox catalysis (Scheme 1). Upon HAT, the resulting carbon radical (vii), stabilized by either a dioxanyl or a dithianyl group, further engages in radical additions to electrophiles.[5] This radical "relay" reaction permits remote C−H functionalization and was employed in the total synthesis of (±)-danshenspiroketallactone (x). The originally generated oxy radical reacts in an energetic cascade with a series of electrophiles to generate multiple bonds in a single-flask operation. This work demonstrated the synthetic potential of a radical cascade reaction.[6]

Scheme 1. Demonstration of Intramolecular HAT Reactions



Previously we reported computational studies of intramolecular 1,5- and 1,6-HAT reactions that demonstrate that the 1,5-HAT process is in general more feasible than the 1,6-HAT process.[7] That is, a six-membered cyclic transition state is both thermodynamically more stable than a seven-membered cyclic transition state and entropically more favored. *Ab initio*

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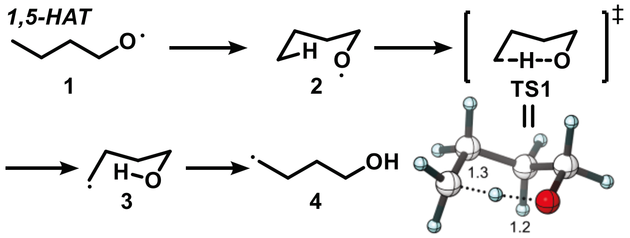
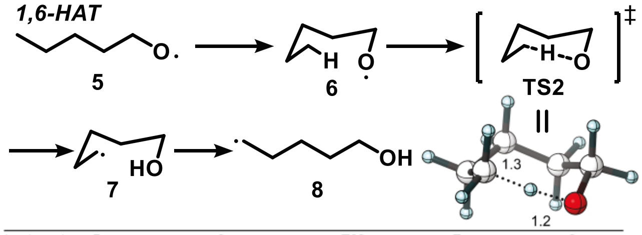
Scheme 2. Energetics of HAT Reactions Using DFT Methods



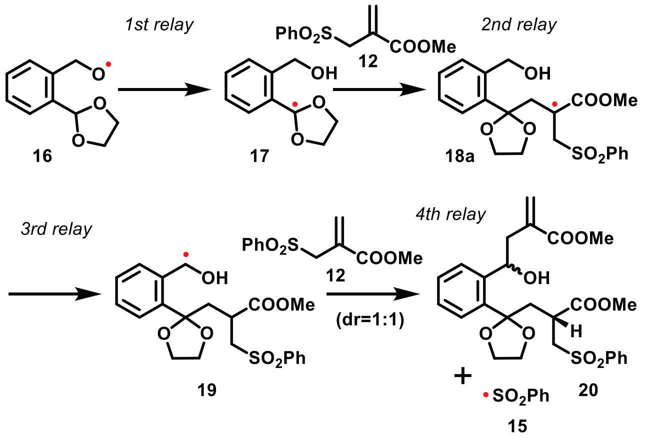
kcal/mol	1	2	TS1	3	4
-TΔS	0.0	0.4	1.7	0.1	-1.2
ΔH	0.0	0.4	9.7	-3.3	-1.7
ΔG	0.0	0.8	11.4	-3.2	-2.9



kcal/mol	5	6	TS2	7	8
-TΔS	0.0	0.8	2.3	0.5	0.9
ΔH	0.0	2.5	9.4	-2.3	-1.8
ΔG	0.0	3.3	11.7	-1.8	-2.9

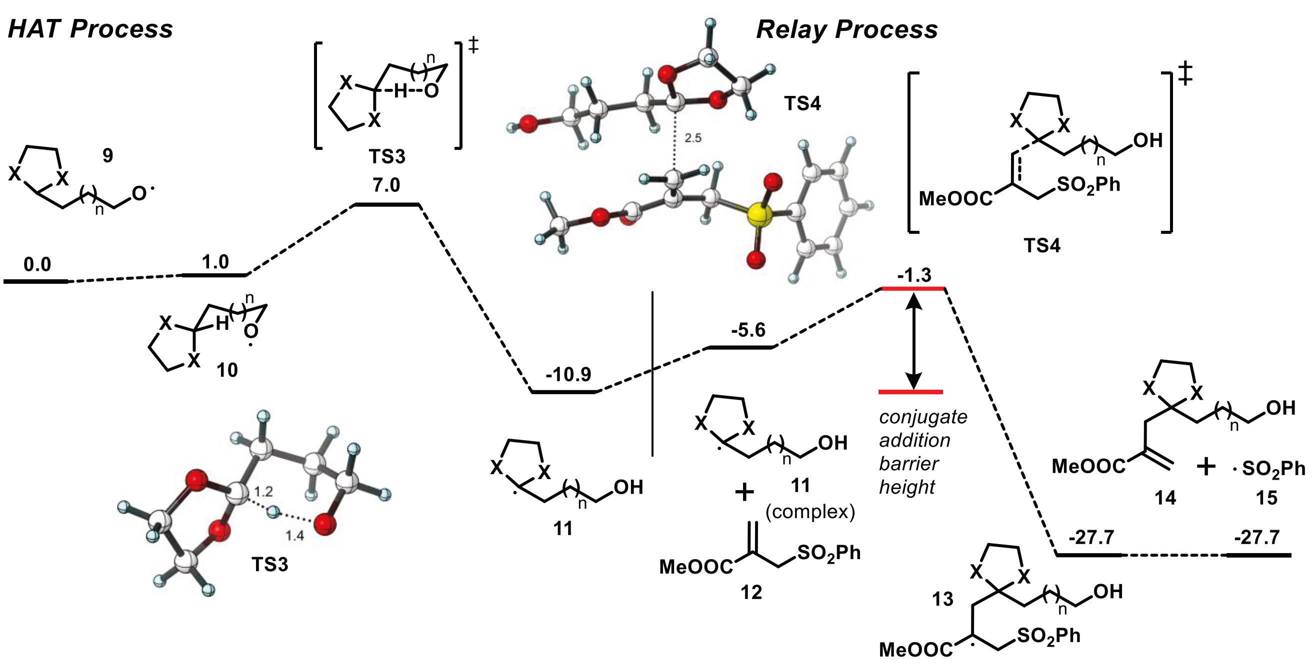
calculations of the intramolecular HAT reactions of butan-1-oxyl and pentan-1-oxyl radicals at the MP2/6-31G(d)//UHF/3-21G level demonstrated that the 1,5-HAT possessed a 19.9 kcal/mol energy barrier, and the barrier of the 1,6-HAT was 21.7 kcal/mol.[4] This 1.8 kcal/mol free energy difference was introduced not from enthalpy ($\Delta\Delta H^{\ddagger} = -0.7$ kcal/mol) but from entropy ($\Delta\Delta S^{\ddagger} = 8.3$ eu, corresponding to 2.5 kcal/mol at rt).[4] Development of DFT methods have now provided an opportunity to reinvestigate the 1,5- and 1,6-HAT process at a more superior computational level and to provide new mechanistic insights.

Scheme 4. Multiple Relay Reaction



The structures of the buta-1-oxyl radical (**1**) and pentan-1-oxyl radical (**2**) were optimized using the DFT method at the uM062X(D3)/6-311++G(2d,p)//uM062X(D3)/6-31G(d) level (Scheme 2).[8] Each corresponding reactive conformation (**2** and **6**) led to an intramolecular HAT cyclic transition state (**TS1** and **TS2**) to generate a primary carbon radical (**4** and **8**). The energy barriers (11.4 and 11.7 kcal/mol) for the HAT

Scheme 3. Free Energy Profile (298 K, 1 atm) of the Radical Relay Reactions



	9 (a-d)	10 (a-d)	TS3 (a-d)	11 (a-d)	11+12 (a-d)	TS4 (a-d)	13 (a-d)	14+15 (a-d)
X=O, n=1, (a)	0.0	1.0	7.0	-10.9	-5.6	-1.3	-27.7	-27.7
X=O, n=2, (b)	0.0	4.5	7.8	-9.2	-3.6	-0.7	-26.9	-26.4
X=S, n=1, (c)	0.0	-2.8	2.4	-19.5	-15.7	-6.6	-27.3	-27.1
X=S, n=2, (d)	0.0	-1.2	1.2	-19.1	-13.8	-5.5	-27.6	-27.1

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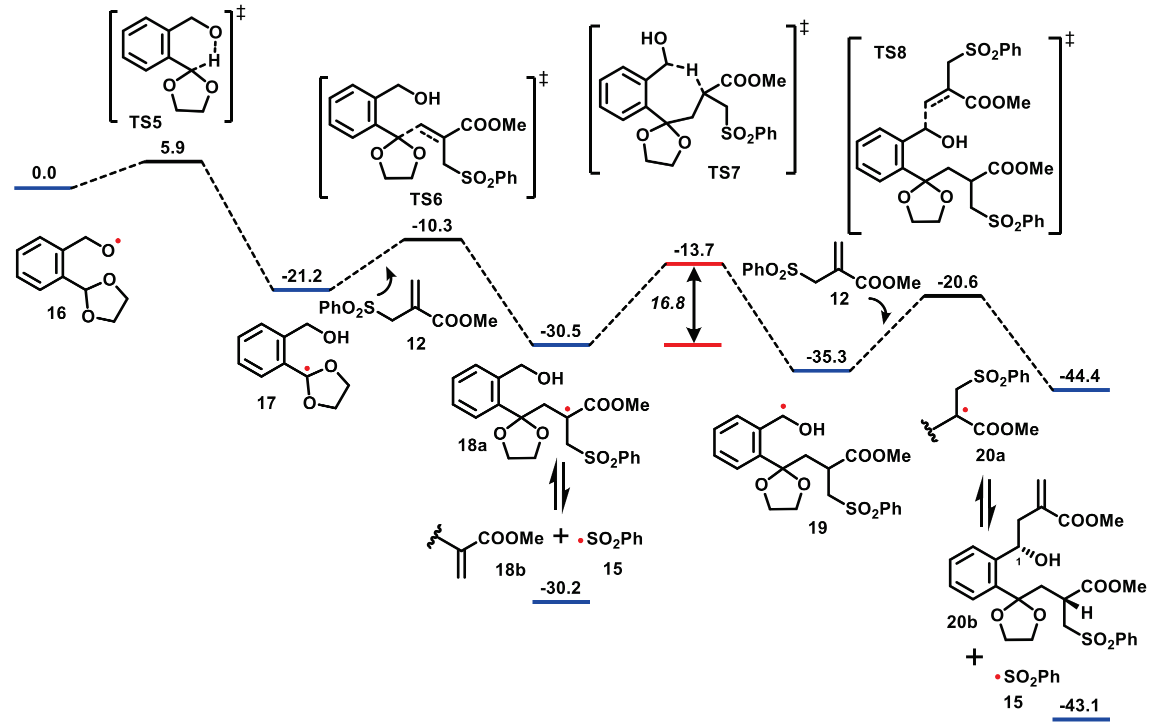
Scheme 5. Free Energy Profile for the Quadruple-Relay Process (298 K, 1 atm)



processes are significantly lower compared to our previous calculations.

We found that activation enthalpies and entropies of 1,5- and 1,6-HAT transition states are similar to each other. Seven-membered transition states generally possess more low energy conformations than six-membered transition states, but the seven-membered cyclic transition state of the HAT process possesses almost the same free energy as the six-membered cyclic transition state.

With this principle in mind, we continued our investigations by introducing either a dioxolanyl (**9a** and **9b**) or a dithiolanyl (**9c** and **9d**) as the radical stabilizing group at the HAT destination (Scheme 3). Not surprisingly, the resulting dioxolanyl (**11a** and **11b**) and dithiolanyl (**11c** and **11d**) radicals in both 1,5- and 1,6-HAT processes have significant thermodynamic preferences. Interestingly, both the 1,5- and 1,6-HAT are also kinetically more facile than those without the radical stabilizing groups (see Scheme 2), as can be demonstrated by their low free energy barriers [see **TS3** (**a**–**d**), Scheme 3]. This result is due to the radical stabilization effect of the dioxolanyl and dithiolanyl groups, and also to the Thorpe–Ingold effect that stabilizes the cyclic conformations, which together resulted in a lower barrier compared with the previous examples (see Scheme 2).

The second relay step (a.k.a. radical addition onto the electrophile) was also investigated. Upon introduction of an allyl sulfone electrophile **12** (Scheme 3), the dioxolanyl (**11a** and **11b**) and dithiolanyl (**11c** and **11d**) radicals underwent conjugate addition followed by an *α*-fragmentation/elimination of **13** to generate the corresponding allylic substituted products **14** and a sulfonyl radical **15**. The radical addition step for dioxolanyl radicals proceeded with a free energy barrier of only 9.6 (**TS4a**, 1,5-HAT) or 8.5 (**TS4b**, 1,6-HAT) kcal/mol, which is comparable to the barrier of the HAT process (7.0 kcal/mol for 1,5-HAT and 7.8 kcal/mol for 1,6-HAT). However, the free energy barrier for the radical addition steps of the dithiolanyl radicals were significantly higher [12.9 kcal/mol for the 1,5-HAT (**TS4c**) and 13.6 kcal/mol for the 1,6-HAT (**TS4d**)], with the conjugate addition step now determining the rate of the overall reaction. This higher energy barrier explains in part why a dithiolane substrate resulted in a lower yield in the experiments. The increased reaction barrier of the second step is likely due to the stability of a dithiolanyl radical. The final *α*-fragmentation/elimination is in equilibrium, and depending on reaction conditions this might permit a further cascade reaction to occur. This proved to be the case as it was possible to introduce multiple relay steps after the initial HAT, as demonstrated in the original report.[5]

In the following example (Scheme 4) upon the first radical addition that generates tertiary radical **18a**, the tertiary radical undergoes a 1,6-HAT to transport the single electron to the benzylic position of **19**, followed by adding to the second equivalent of **12**. An elimination then occurs that leads to a double addition adduct **20** in 56% overall yield after oxidation.[5] We have now investigated this relay process computationally. Upon generation of benzylalkoxy radical **16**, a facile 1,5-HAT (**TS5**, 5.9 kcal/mol, Scheme 5) generates benzylic radical **17**. Addition to the radical acceptor **12** leads to **18a** that is in equilibrium with **18b**. **18a** undergoes a seven-membered 1,6-HAT transition state (**TS7**) and then generates a benzylic radical (**19**). Final addition of another equivalent of **12** followed by *α*-fragmentation furnishes the final product **20b**. The 1,6-HAT process is now the rate-limiting step (16.8 kcal/mol free energy barrier) in this "energetic cascade". The multiple migration of the original radical from oxy- to dithiolanyl-, *β*-sulfonyl-, benzyl-, *β*-sulfonyl-, and finally sulfonyl- are accompanied by bond relocation.

In summary, 1,5- and 1,6-HAT reactions have been further investigated using DFT methods and as shown have similar reactivity. Importantly, installation of radical stabilizing groups leads to the generation of a multiple-stage process involving multiple chemical bond formations. In order to achieve this energetic cascade, electrophiles must be selected in a manner that a radical can be generated at a new position upon each transfer without being quenched. Via this concept, multiple bond construction can be achieved in a single-flask in a "relay" manner, to facilitate the construction of complex molecular structures.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.9b02023.

> General computational methods; energetics of all computed species; Cartesian coordinates of all computed species; references to computational program (PDF)

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Notes

The authors declare no competing financial interest.

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(8) All calculations were performed using Gaussian 09, Revision A.02 (for full citation, please see Supporting Information).