

Allyl Zincation of Vinyl Metals: A Computational Study

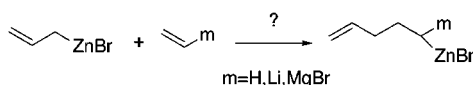
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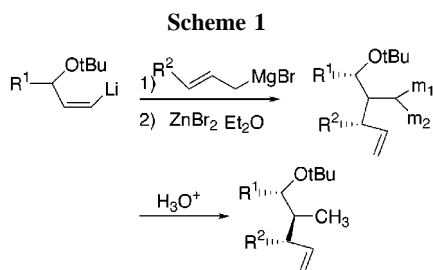
Received July 21, 1999

ABSTRACT



The allyl zincation of vinyl lithium or Grignard reagents was studied computationally and compared to the allyl zincation of ethylene. The key step is a preorganization of the reagents via Zn–Br–Li (or Mg) coordination, which is also apparent in the transition structures. The experimentally observed diastereoselectivity when substituted (*E*- or *Z*-)vinyl lithium reagents are added to crotyl zinc bromide may also be explained in terms of preferentially stabilized transition structures with *cisoid* allyl moieties.

We recently reported¹ and reviewed² that the addition of various allylmetals to vinylmetal derivatives is a straightforward route to 1,1-bis-metalated species (Scheme 1)



whereby up to four stereogenic centers can be created in a single step. This methodology was successfully applied to the homochiral synthesis of α -substituted aldehydes.³

However, these very interesting synthetic results are puzzling because of the efficiency of this reaction⁴ as

compared to the addition of allylmetals to nonmetalated olefins. Indeed, it is known that ethylene reacts under pressure with allylic magnesium halides⁵ in ether (40–70 atm, 20–80 °C, 2–100 h) or with various allylzinc derivatives⁶ to afford the corresponding unsaturated organometallic compounds. The fundamental question is then why a metalated alkene is more reactive toward the addition of an allylmetal (the two nucleophilic species readily react below

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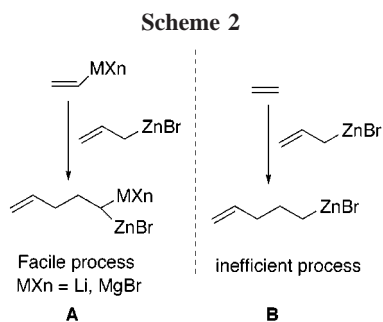
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−40 °C to give a single product, Scheme 2A) than a nonmetalated one (Scheme 2B).



To answer this critical question, we decided to compare the energy profile of the two simplest reactions described in Scheme 2 by using computational methods. Geometries of all stationary points were fully optimized at the Hartree–Fock level using analytical energy gradients as implemented in the Gaussian 94 program package.⁷ As there is no electron pair separation, the effect of neglecting electron correlation on the geometries is expected to be small.⁸ All geometry optimizations utilized 6-31+G* (carbon, hydrogen, and lithium) and 3-21G (zinc, bromine, and magnesium) basis sets.⁹ Stationary points were characterized by analytical vibrational frequency analyses to determine their nature as minima (the number of imaginary frequencies, NIMAG, equals zero) or transition structures (NIMAG = 1). Zero-point vibrational energies (ZPVE) were scaled by 0.89¹⁰ and are included in our final energy evaluations. Single-point energies based on these geometries were evaluated at the density functional level of theory (DFT)¹¹ utilizing Becke's three-parameter exchange-correlation functional¹² including the nonlocal gradient corrections described by Lee, Yang, and Parr (LYP),¹³ in conjunction with the 6-311+G* basis set on all atoms. Standard notation is used; i.e., “//” means energy computed at the // geometry. All energy comparisons refer to the B3LYP/6-311+G*/HF/6-31+G* (C, H, Li) and 3-21G (Zn, Mg, Br) + ZPVE level of theory. All optimized structures and absolute energies are collected in the Supporting Information; the structures depicted in the various

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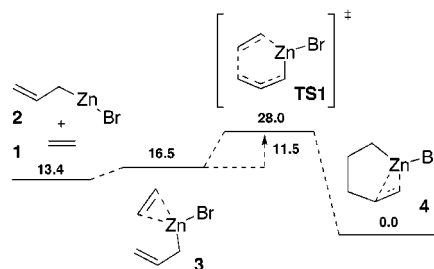
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schemes are drawn to represent the apparent bonding interactions as closely as possible.

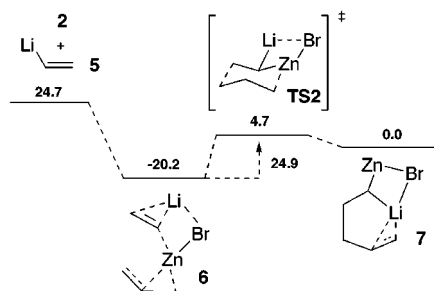
The computed potential energy hypersurface for the addition of ethylene (**1**) to allylzinc bromide (**2**) (Schemes 2B and 3) reveals that the formation of the initial complex

Scheme 3. Computed Allylzincation of Ethylene (Energies in kcal mol^{−1})



(**3**) is endothermic; i.e., there is no favorable preorganization of the two reactants. On the other hand, **2** and vinyl lithium (**5**) (Schemes 2A and 4) form a rather strong complex (**6**)

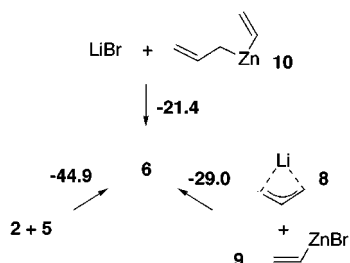
Scheme 4. Computed Allylzincation of Ethenyllithium (Energies in kcal mol^{−1})



bringing the two reactants in close contact. This complexation (or template effect)¹⁴ between **5** and **2** (via the Br atom) is the key step of this reaction, since the metalated carbon (C–Li) of **5** is already coordinated to the zinc moiety. A natural population analysis¹⁵ reveals the following bond orders (in e): Li···Br = 0.3; Zn···Br = 0.2 due to large high charge separation: Li = +0.9; Zn = +1.4; Br = −0.8; vinylic and allylic carbons = −0.9 to −1.0. The addition of **2** to **5** leads then to the geminal bis-metallic derivative (**7**) by a carbometalation process (zinc-ene reaction) via a chairlike transition state (**TS2**) with a barrier of 24.9 kcal mol^{−1}. The activation enthalpy for the boat transition structure is 34.2 kcal mol^{−1} (not shown in Scheme 4).

An alternative process would be the initial formation of a mixed zinc vinyl–allyl species, undergoing a rearrangement akin to the Claisen rearrangement where zinc plays the role of oxygen.^{1a} But here again, the presence of LiBr in the reaction mixture drives the reaction to the same complex (the same result is obtained starting from vinyl zinc bromide and allyllithium; Scheme 5). Hence, irrespective of the nature of the reactants at the beginning, the driving force of the

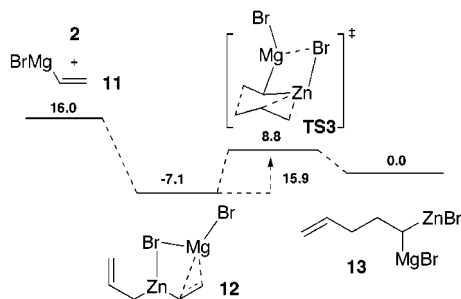
Scheme 5. Computed Formation of the Allylvinyllithium Bromide Complex from Different Organometallic Species (Energies in kcal mol⁻¹)



reaction is the complexation to the LiBr–vinyl–allyl–zinc species. Although the product formation step in this process is endothermic, it is likely that further aggregation drives this reaction. Indeed, it is quite conceivable that the coexistence of an organolithium with an organozinc bromide on the same carbon center might lead to a dizincacyclobutane¹⁶ or an even more highly aggregated complex. Moreover, we noted before that this reaction is reversible when the mixture is left at room temperature overnight or is heated for a few hours.^{1a}

We also found experimentally that the reaction is faster when ethenylmagnesium halide (**11**) is used instead of ethenyllithium. To rationalize this observation, we have investigated the magnesium case as well (Scheme 6). The

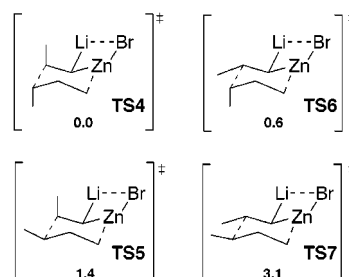
Scheme 6. Computed Allylzincation of Ethenylmagnesium Bromide (Energies in kcal mol⁻¹)



necessary precomplexation also exists between the reactants **11** and **2**, but it is notably less exothermic than in the case of **5**. The structure of the vinylmagnesium bromide–allylzinc bromide complex (**12**) is similarly ionic as the complex discussed in Scheme 4 (in e): Mg = +1.6; Zn = +1.4; Br = -0.8; vinylic and allylic carbons = -1.0. With the assumption that all of the above transformations only occur efficiently when precoordination precedes the carbon–carbon bond formation, the differences in activation enthalpies for the reaction of vinyl lithium versus vinylmagnesium bromide, 9 kcal mol⁻¹ (TS3 versus TS2), respectively, may be taken to explain the differences in relative reaction rates favoring the transformation depicted in Scheme 6.

As the addition of **2** to **5** occurs via a chairlike transition state, we were wondering if it is possible to understand the diastereoselectivity of this process. Indeed, we found experimentally that the addition of crotylzinc halide to the stereochemically pure (*Z*)- or (*E*)-methylvinyl lithium compounds leads to the *anti* and *syn* products, respectively, with notably very high diastereoselectivities (95/5 to 92/8) for acyclic systems. As the diastereoselectivity observed in this crotylmatalation may be accounted for by a preferential or kinetically favored *Z* configuration of the crotylmetal species in the chairlike transition state, we decided to compare the energy profile of the *E* and *Z* forms of the crotylmetal in this carbometalation reaction. Indeed, when we start from (*Z*)-propenyllithium, the *Z* configuration of the crotyl reagent leads to a transition state 1.4 kcal mol⁻¹ (TS4) lower in relative energy than that starting from the *E* isomer (TS5). When we start from (*E*)-propenyllithium, the same holds true with an even larger energy difference of 2.5 kcal mol⁻¹ more (TS6 versus TS7). As a consequence, the transition states for the different approaches vary significantly in their relative energies (Scheme 7), leading to the experimentally observed high diastereoselectivities.

Scheme 7. Computed Transition States for the Reaction of Propenyllithium with Crotylzinc Bromide (Energies in kcal mol⁻¹)



Our computational analyses of the reactions of allyl- and vinylmetals show that the formation (or absence!) of initial complexes is decisive. This proximity effect is amplified by the fact that the *same* complex may form from different sources. Hence, the addition of the allyl moiety across the vinyl part occurs via a chairlike transition state to give the polymetalated species.

Application of this precomplexation to other systems is now being studied and will be reported in due course.

Acknowledgment. This research was supported by the Deutsche Forschungsgemeinschaft (fellowship for P.R.S.) and the Fonds der Chemischen Industrie. Generous allotment of computer time from the RRZN Hannover is gratefully acknowledged.

Supporting Information Available: Optimized structures and absolute energies. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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