Nickel-catalyzed Reactions of Enone with Ethylene

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Abstract. The reaction of (E)-1-phenylbut-2-en-1-one with ethylene in the presence of a catalytic amount of Ni(cod)$_2$ and PCy$_3$ at room temperature gave two kinds of three-component addition products; one is 1,6-enone composed of an enone and two ethylene molecules, and the other is 1,5-diketone composed of two enones and an ethylene. The reactions might proceed via oxidative cyclization of an enone and an ethylene with nickel(0).

1. Introduction
Formation of a carbon-carbon bond by the addition of C-H bonds across carbon-carbon unsaturated compounds, such as alkynes and alkenes, constitutes a particularly variable strategy, because it is one of the most atom-economical reactions to construct a carbon-carbon bond. For one thing, direct conjugate addition reactions of enolizable substrates, such as 1,3-dicarbonyl compounds to $\alpha,\beta$-unsaturated carbonyl compounds, are employed for forming a carbon-carbon bond [1]. For another, transition metal catalyzed direct conjugate additions of terminal alkynes to enones have been reported as well (Scheme 1) [2-6].

Scheme 1. Transition metal catalyzed direct conjugate addition reactions of terminal alkynes to enones.

In addition, construction of carbon-carbon bonds between enones and alkynes can also be achieved by nickel-catalyzed three-component cycloaddition reactions (Scheme 2). Ikeda et al. developed nickel-

Scheme 2. Ni-catalyzed three-component cycloaddition reactions of enones with alkynes.

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catalyzed reactions of an enone with two alkenes to afford cyclohexadiene derivatives [7; 8]. Nickel-catalyzed intramolecular reactions of an alkyne and two enones, yielding cyclohexene derivatives, were reported by Montgomery et al. [9]. In contrast, it has been believed to be difficult that an alkenyl group is introduced into the $\beta$-position of an enone by the addition of C-H bonds of simple alkenes as reported for terminal alkynes, since a C-H bond of simple alkenes is much less reactive than that of the terminal alkynes. We recently demonstrated the first example of a nickel-catalyzed direct conjugate addition reactions of simple alkenes, such as styrene, to enones, which is a very straightforward process to introduce an alkenyl group to the $\beta$-carbon of enones by the addition of a carbon–hydrogen bond (Scheme 3) [10; 11]. In this reaction, oxidative cyclization of alkenes and enones with nickel(0), giving a nickelacycle intermediate [12-16], was proposed as a key reaction step.

As a part of investigation on the reactivity of enones with alkenes, we focused attention on a Ni-catalyzed reaction of enones with ethylene, since ethylene is one of the important industrial feedstock. To date, a variety of reactions have been developed to convert ethylene into more valuable chemicals, and the hydrovinylation reaction of alkenes mediated by transition metal hydride complexes is regarded as one of the most useful reactions for the introduction of ethylene into alkenes. However, the isomerization of terminal alkenes to internal alkenes also took place under the reaction conditions using transition metal hydride species (Scheme 4), therefore, a limited number of alkenes, such as vinylarenes, cyclic dienes, and norbornenes, are available for hydrovinylation reactions [17].

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We, thus, investigated the reactivity of $(E)$-1-phenylbut-2-en-1-one (1) with ethylene in the presence of Ni(0) catalyst, resulting in the formation of three-component addition products [18]. To the best of our knowledge, this is the first example of the three-component addition reactions of enones with alkenes, which afford terminal alkenes [11; 19; 20].

2. Results and Discussion
In the presence of Ni(cod)$_2$ and PCy$_3$ (cod = 1,5-cyclooctadiene, Cy = C$_5$H$_{11}$), the reaction of 1 with 5 atm of ethylene at room temperature in C$_6$D$_6$ resulted in the formation of a mixture of 1,6-enone 2 and 1,5-diketone 4 in 7% and 41% yield, respectively (Table 1, Run 1) [21]. Both products 2 and 4 were three-component addition compounds; the enone 2 was composed of an enone and two ethylenes, whereas the ketone 4 consisted of two enones and an ethylene. With elevating the reaction temperature to 80 °C, the yields of 2 and its isomer 3 increased and the formation of 4 was suppressed in 19% yield (Run 2). The yield of 2 was somewhat improved to 30% under a higher (8 atm) ethylene pressure conditions (Run 3). The reaction was carried out under a much higher ethylene pressure (30 atm) with much diluted solution of 1 (0.04 M). The selectivity of 2 and 3 toward 4 was, as a result, found to be improved, and finally, a mixture of 2, 3, and 4 was isolated in 74% yield (Run 4).
Table 1. Reaction of 1 with ethylene in the presence of Ni(cod)$_2$ and PCy$_3$.

A plausible reaction mechanism, although any nickelacycle intermediates were not directly observed at all, is depicted in Scheme 5. The oxidative cyclization of an enone and ethylene with a nickel(0) species generates a $\eta^3$-oxaallylnickelacycle intermediate (A). The formation of the corresponding nickelacycle by the intramolecular oxidative cyclization of an enone and an alkene with nickel(0) has been reported [13]. The direct conjugate addition product (B), the analogue of which was obtained by employing styrene instead of ethylene as an olefin partner [10], was not generated at all, indicating that $\beta$-hydrogen elimination from A did not take place.

Scheme 5. A plausible mechanism for the formation of three-component coupling products.
Instead, insertion of either an enone or an ethylene to A generates a seven-membered nickelacycle intermediate (C) or (D), respectively. The seven-membered nickelacycle intermediate C would undergo β-hydrogen elimination followed by reductive elimination to give a 1,5-diketone product (E). It should be mentioned that the seven-membered nickelacycle intermediate C might be formed by the conjugate addition of A to an enone, since the conjugate addition of a six-membered nickel enolate to an enone proceeded [22; 23].

Likewise, the other seven-membered intermediate D would also undergo β-hydrogen elimination followed by reductive elimination, giving a mixture of 1,6-enone compound (F) and its isomeric 1,2-enone (G). As an alternative reaction path to generate D, the oxidative cyclization of (η²-CH₂=CH₂)₂Ni(PCy₃) followed by the insertion of an enone into nickel–carbon bond is also possible. In fact, at the end of the reaction, the formation of (η²-CH₂=CH₂)₂Ni(PCy₃) was confirmed [24].

3. Conclusions

We demonstrated the first example of the reaction of an enone with two ethylene molecules in the presence of Ni(cod)₂ and PCy₃. This reaction product, a 1,6-enone with a terminal alkenyl moiety, can be regarded as a cross-trimerization compound composed of alkenes with ethylene. In addition, at a lower temperature, the reaction of two enones with an ethylene gave a 1,5-diketone compound as a major product.

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