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Intramolecular carbonyl-ene reaction of citronellal to isopulegol over $ZnBr_2$-loading mesoporous silica catalysts

Shohei Imachi [1], Kisho Owada, Makoto Onaka *

Department of Chemistry, Graduate School of Arts and Science, The University of Tokyo, Meguro, Tokyo 153-8902, Japan

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Abstract

We report the preparation of $ZnBr_2$-loading mesoporous catalysts and their application to the intramolecular carbonyl-ene reaction of (+)-citronellal to (−)-isopulegol. The mesoporous catalysts were characterized by N_2 adsorption–desorption isotherms, X-ray powder diffraction (XRD), scanning electron microscopy (SEM), and inductively coupled plasma atomic emission spectrometry (ICP-AES). Among a series of mesoporous supports, C8-HMS, which was synthesized from $Si(OEt)_4$ via a sol–gel process in the presence of octylamine as a templating agent, was found to be an optimal support to load $ZnBr_2$ without damage of inherent mesoporosity of the support. The $ZnBr_2$ loaded on C8-HMS ($ZnBr_2$/C8-HMS) showed higher catalytic activity and diastereoselectivity than $ZnBr_2$ on other HMS with different particle and pore sizes, MCM-41, mesoporous alumina, and Al-HMS. The amount of zinc ions eluted into the solution phase from $ZnBr_2$/C8-HMS was only at a less than 1 ppm level. The results suggested that clumped $ZnBr_2$ was no longer formed on the mesoporous silica surface. The $ZnBr_2$/C8-HMS catalyst which had been washed well with excess EtOH still contained zinc species, but had neither catalytic activity nor bromide ions. It was concluded that at least two different kinds of Zn sites existed on the surface of $ZnBr_2$/C8-HMS; one site was the crystallite $ZnBr_2$ which was finely dispersed on the silica surface, and the other was oxygenated zinc species such as $Zn(OSi{\equiv})_2$ and/or $Zn(OH)(OSi{\equiv})$.

Keywords: (+)-Citronellal; Intramolecular carbonyl-ene reaction; HMS; $ZnBr_2$; Mesoporous catalyst

1. Introduction

As the skeleton of a menthol molecule has three stereogenic centers, eight diastereomers are possible. However, among the isomers (−)-menthol is only one beneficial isomer as an ingredient for cigarettes, chewing gums, toothpastes, pharmaceutical and personal-care products [1], and 4500 t a year of the compound is consumed worldwide. In the current menthol industry, (−)-menthol is mainly provided by three routes [2]: (1) extraction from natural mint in China and Brazil; (2) synthesis of racemic menthol from *m*-cresol via the formation of thymol (2-isopropyl-5-methylphenol) and its reduction with hydrogen, followed by optical resolution; (3) chemical synthesis from myrcene through asymmetric isomerization of diethylgeranylamine with an Rh-BINAP catalyst and an intramolecular carbonyl-ene reaction as key steps (the Takasago process) [3].

In the Takasago process, myrcene, produced by thermal cracking of β-pinene, reacts with diethylamine in the presence of a catalyst of *n*-BuLi to give diethylgeranylamine stereoselectively. Asymmetric isomerization of diehtylgeranylamine to citronellal (*R,E*)-diethylamine by a chiral rhodium/(*S*)-BINAP catalyst is the most remarkable step in the Takasago process. Additionally, we should consider another step of intramolecular cyclization of (*R*)-(+)-citronellal to (−)-isopulegol an equally important stage, because the cyclization of citronellal can afford four diastereoisomers, among which (−)-isopulegol is only a desirable precursor to (−)-menthol.

In the Takasago process, isomerization of (+)-citronellal to (−)-isopulegol, which is classified as an intramolecular carbonyl-ene reaction, was originally performed in up to 92% diastereoselectivity in the presence of $ZnBr_2$, which had been discovered by Nakatani and Kawashima [4]. However, there were some shortcomings that the reaction requires a stoichiometric amount of solid $ZnBr_2$, some of which were dissolved in organic solvents such as CH_2Cl_2 and benzene. Recently Takasago patented a new homogeneous catalyst of tris(2,6-diarylphenyloxy)aluminum for the cyclization of (+)-citronellal

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* Corresponding author. Tel.: +81 3 5454 6595; fax: +81 3 5454 6998.
E-mail address: conaka@mail.ecc.u-tokyo.ac.jp (M. Onaka).

[1] Research Fellow of the Japan Society for the Promotion of Science.

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[5]. Although this catalyst promotes the cyclization in over 95% yield of (−)-isopulegol with almost 100% diastereoselectivity, the catalyst is difficult to be separated from the reaction mixture and to be reused. Therefore, discovering a new heterogeneous catalyst system has been paid much attention to by many chemists, and several heterogeneous catalysts for the cyclization have been reported.

Corma et al. reported that water-tolerant and Lewis acidic Sn-β zeolite in which tin ions were isomorphically substituted into the β zeolite framework worked as an efficient catalyst for the cyclization of (+)-citronellal [6]. The catalyst recorded a turnover number of 1350 per tin ion in 83% diastereoselectivity without elution of tin ions.

Zirconium ion-exchanged montmorillonite was also an excellent solid catalyst for the cyclization with 90% selectivity, and was able to be reused at least five times with the same activities [7]. Zr-β zeolite, which was synthesized by the incorporation of zirconium ions into β zeolite, also showed high diastereoselectivity [8].

Typical porous silica-based catalysts accelerated the cyclization of (+)-citronellal as well: the cyclization was drastically improved by using H_3PO_4- or heteropolyacid-loading silica gel, while both catalysts showed only moderate diastereoselectivities [9,10]. Galvagno et al. prepared Zn(II)-loading catalysts by impregnation of amorphous silica with a solution of $ZnBr_2$, followed by drying, and the catalysts were found to show up to 86% diastereoselectivity [11,12]. According to their investigation, the silica surface consists of both physically adsorbed $ZnBr_2$ and Zn(II) sites of zinc oxy-hydroxide and/or $Zn(OSi\equiv)_2$. The Zn(II) sites are the most active for the cyclization, but the physically adsorbed $ZnBr_2$ is required to attain high diastereoselectivity. In other words, the $ZnBr_2$ site was less active but more diastereoselective than the Zn(II) sites. Then, it is easy to envisage that more active and higher diastereoselective catalysts can be realized if support materials are covered with well-dispersed $ZnBr_2$ salts on the surface.

In recent years, a lot of mesoporous materials have been developed such as silica, aluminosilicate, and alumina. Generally, mesoporous materials which have uniform mesopores and high specific surface areas are prepared in the presence of proper template agents through a sol–gel process. Compared with the use of amorphous or microporous supports, that of mesoporous supports provides us several remarkable advantages: (1) the nano-sized uniform pore structure prevents $ZnBr_2$ crystal from agglomerating, (2) the large surface area enables the support to hold a large amount of active species on the surface, and (3) the size of mesopore is large enough to diffuse a variety of organic substrates and products smoothly.

To make the best use of these features leads to the preparation of various effective catalysts. For example, we have already reported that MoO_3 supported on HMS showed remarkable catalysis for olefin metathesis against MoO_3 on normal silica [13]. It was also demonstrated that Re_2O_7 finely dispersed on mesoporous alumina more effectively catalyzed the metathesis of terminal and inner olefins than Re_2O_7 on γ-alumina [14]. More recently, we discovered that methyltrioxorhenium on $ZnCl_2$-modified mesoporous alumina catalyzed the metathesis not only of simple olefins but also of olefins functionalized with ester, carbonyl, and halogen groups [15].

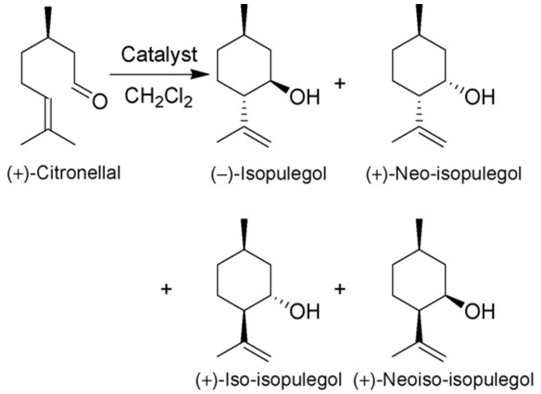

Fig. 1. Four diastereoisomers from the cyclization of (+)-citronellal.

This article describes the preparation and characterization of $ZnBr_2$ loading mesoporous catalysts in detail and their application for the cyclization of (+)-citronellal to (−)-isopuregol in a high diastereoselective way (Fig. 1).

2. Experimental

2.1. General

Commercially available (+)-citronellal (Tokyo Kasei Kogyo) was distilled before use. CH_2Cl_2, EtOH and CH_3CN (Kanto Chemical) were dried over Molecular Sieves 4A. SiO_2 (Fuji Silysia Chemical, CARiACT Q-3), $Si(OEt)_4$ (Tokyo Kasei Kogyo), colloidal silica (Aldrich, HS-40, 40 wt% suspension in water), *n*-octylamine (Tokyo Kasei Kogyo), *n*-dodecylamine (Tokyo Kasei Kogyo), *n*-hexadecylamine (Kanto Chemical), *n*-hexadecyltrimethylammonium chloride (Kanto Chemical), Al(O-*s*-Bu)$_3$ (Tokyo Kasei Kogyo), NH_4OH (Kanto Chemical, 30 wt%), 1-propanol (Kanto Chemical), lauric acid (Kanto Chemical), Al(O-*i*-Pr)$_3$ (Kanto Chemical) and $ZnBr_2$ (Kanto Chemical) were used without further purification. Infrared (IR) spectra were recorded on a JASCO FT550 FT-IR spectrometer. ^1H NMR spectra were recorded on a JEOL JNM-GSX270 (270 MHz) or a JEOL JNM-GSX500 (500 MHz) spectrometer; chemical shifts (δ) are reported in parts per million relative to tetramethylsilane. Splitting patterns are designed as s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; br, broad. ^{13}C NMR spectra were recorded on a JEOL EX270 (68 MHz) spectrometer with complete proton decoupling. Chemical shifts were recorded in parts per million relative to tetramethylsilane with the solvent resonance as internal standard ($CDCl_3$; δ 77.0 ppm). N_2 adsorption–desorption measurements were performed at −196 °C with a Belsorp 28SA (Bel Japan, Inc.) using static adsorption procedures. Samples were outgassed at 400 °C and 1.3 Pa for 12 h prior to analysis. Specific surface area (S.A.) was determined by the BET method. Pore diameter (P.D.) was calculated by means of the BJH method. Gas chromatography analysis (GC) was carried out with a Shimadzu GC-8A equipped with an FID detector and a 25 m OV-1 chemically bonded capillary column. X-ray powder diffraction