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Vapour-phase synthesis of 2-methyl- and 4-methylquinoline over BEA* zeolites

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Abstract

4-Methylquinoline and 2-methylquinoline were synthesized from acetaldehyde and aniline in the gas phase over BEA* zeolite catalysts. High combined yields of 2- and 4-methyl-substituted quinolines were obtained with H-BEA* zeolite and with BEA*-F synthesized in fluoride medium, with 4-methylquinoline being the predominant isomer. Postsynthesis fluorination of the H-BEA* with ammonium fluoride leads to dealumination and formation of extra-framework aluminium fluoride compounds. Product selectivities changed with time over this catalyst, such that 2-methylquinoline became the predominant product. New insight into the reaction mechanism is offered, and previous propositions can be rationalized based on these new results.
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1. Introduction

Nitrogen-containing heterocyclic compounds, such as quinoline and alkylquinolines, are important intermediates in the production of pharmaceuticals, herbicides, fungicides, dyes, etc. [1]. Until now, quinoline has been recovered from coal tar with sulfuric acid, followed by precipitation with ammonia [1]. Several methods of synthesising quinolines using homogeneous acid catalysts exist, but they produce toxic waste streams [2]. These methods include conventional routes, including Skraup, Döbner–von Miller, Gould–Jacobs, Knorr, Beyer, Friedländer, and Pfitzinger syntheses [3–5]. In recent years several new approaches have been developed for synthesis in the liquid phase using transition metal-based Lewis acid catalysts. Ruthenium, rhodium, palladium, and iron complexes catalyze the formation of 2,3-substituted quinolines from nitrobenzene and aldehydes or alcohols in the presence of CO [6–9]. Conversion of

diallylamines with $Co_2(CO)_8$ as a catalyst in a heteroannulation reaction also yield 2,3-substituted quinolines [10]. Good yields have also been obtained with a ruthenium–tin complex catalyzing an amine exchange reaction between anilines and trialkylamines, followed by Schiff-base dimerisation and heteroannulation. With *m*-toluidine, the 7-substituted isomer is favoured [11,12]. $Ln(OTf)_3$ and $Sc(OTf)_3$ have been used to promote three-component coupling reactions between aldehydes, amines, and dienes or alkenes. These Lewis acid catalysts were active in imine formation and successive imino Diels–Alder-type reactions. High yields of poly-substituted tetrahydroquinolines were reported [13,14].

The quest for green alternatives for chemical reactions is motivated by our growing awareness of their potential impact on the environment. Reactions in the vapor phase with heterogeneous catalysts offer several advantages over liquid-phase processes, including easy catalyst recovery, continuous processing, and absence of acid waste streams. A number of attempts to synthesize quinolines in the vapor phase have been successful [15–20]. The industrial relevance of gas-phase quinoline synthesis was recently demonstrated when McAteer

et al. were awarded a world patent [15]. They reported formation of 8-methylquinoline in good yield from *o*-toluidine and a mixture of formaldehyde, acetaldehyde, and water at 450 °C over amorphous aluminosilicate and zeolite catalysts. Zeolites with BEA* topology performed slightly better than zeolites with MOR, FER, or MFI topologies. The main quinoline byproducts are, in order of importance, 3,8-dimethylquinoline, 6,8-dimethylquinoline, and 2,8-dimethylquinoline. Aniline reacted with crotonaldehyde over fluor-containing aluminosilicate catalyst at 450 °C to yield predominantly 4-methylquinoline, with 2-methylquinoline as only a minor impurity [20]. Campanati et al. found that the reaction of 2-ethylaniline with ethyleneglycol over an acid-treated commercial K10 montmorillonite catalyst yielded mainly 2-methyl-8-ethylquinoline [18,19]. A reaction pathway was proposed in which ethylene glycol is converted to crotonaldehyde through dehydration and condensation and subsequently undergoes conjugate or Michael-type addition, followed by electrophilic aromatic substitution. It is surprising that in this instance the 2-substituted isomer is formed, in contrast to the 4-substituted isomer formed as major product by other methods. Michael addition of 2-ethylaniline to crotonaldehyde is apparently favoured over an initial imine-forming reaction of aniline with crotonaldehyde. The regioselectivity of the reaction of the aniline base with the α,β-unsaturated aldehyde may be influenced by the reaction temperature, acidity of the catalyst, alkylation of the aniline base, and choice of aldehyde reagents that condense to form the α,β-unsaturated aldehyde. Campanati et al. suggested that an alternative to the imine route, involving regiospecific ortho-alkylation of the aniline base with the β-carbon of the α,β-unsaturated aldehyde, leads to the 4-substituted quinoline. They argued that a substituted aniline, such as 2-ethylaniline, would experience steric hindrance at the amine function and preferentially form the 2-substituted isomer via Michael addition [18]. But it is not clear why the 2-ethylaniline would not undergo Friedel–Crafts acylation with α,β-unsaturated aldehyde, which would give the 2-substituted isomer. The feasibility of regiospecific ortho substitution of a secondary aniline without a substituent in the para position has been demonstrated using boron trichloride as a catalyst and benzene as a solvent [33]. In summary, to date no coherent explanation has been given for the regioselectivity of the reaction between aniline bases and aldehyde reagents or their condensation products.

This paper reports the high activity and selectivity of BEA* zeolite catalysts for the synthesis of methyl-substituted quinolines from aniline and acetaldehyde. The influence of fluorination of the zeolites on the activity and selectivity is addressed. New insight into the reaction mechanism is gained from these new results, as well as from recent literature on the synthesis of heterocyclic nitrogen-containing compounds [34]. Previous propositions can be rationalized based on our findings.

2. Experimental

The fluorination of the BEA* zeolite was carried out as follows. A 10-g sample of a commercial zeolite (PQ) powder with Si/Al: 21.6 was impregnated with ca. 17 mL of a 2.0 M aqueous solution of NH_4F by the incipient wetness method and dried overnight at 60 °C. (Another way of introducing F^- into the catalyst is to use HF as the mineralizing agent in the hydrothermal synthesis of a zeolite [21].) A BEA*-F zeolite was crystallized from a gel with the following relative molar amounts: TEAOH:14 TEOS:25 Al:1 H_2O_2:8.6 H_2O:189 HF:14, adapting a recipe for a Ti-Beta zeolite synthesized in fluoride medium by replacing Ti with Al [22]. The BEA*-F zeolite crystals were calcined at 500 °C, and the crystallinity was confirmed by X-ray diffraction. Catalysts were activated at temperatures above 450 °C in dry air. Before catalytic testing, the temperature was lowered and the reactor was flushed with nitrogen. In the activation procedure for NH_4F-treated H-BEA* (NH_4F-BEA*), NH_4F was allowed to decompose at 250 °C in dry air, releasing ammonia, after which the activation temperature was set.

The reaction gas mixture was composed of water, acetaldehyde, and aniline in nitrogen carrier in molar ratios of 4:4:1. The gas feed with water and acetaldehyde and the gas feed with aniline were led seperately to the reactor vessel so that mixing of the reagents set in shortly above the catalyst bed. The gas feed was passed over a 5-mL catalytic bed at a GHSV of 900 h^{-1}. Aniline was administered at a rate of 0.2 mL h^{-1}. Reaction products were condensed at −78 °C and analyzed by gas chromatography. A blank reaction over inert SiC at 450 °C produced only trace amounts of acetaldehyde anil (AA). Mass spectrometry analysis confirmed structure assignments. Solid-state ^{29}Si and ^{27}Al MAS nuclear magnetic resonance (NMR) spectra of selected samples were recorded on a Bruker AMX-300 (7 T) spectrometer operating at 79.5 and 104.26 MHz, respectively. Chemical shifts were referred to tetramethylsilane and $Al(NO_3)_3 \cdot 6H_2O$, respectively.

3. Results

Table 1 provides data on aniline conversion; product selectivities for 2-methylquinoline (2MeQ), 4-methylquinoline (4MeQ), quinoline, and *N*-ethylaniline (EA); and combined yields of quinolines. With BEA* catalyst activated at 500 °C, a yield of 83% was obtained at 450 °C after 4.5 h on stream (HOS). Table 2 lists the best yields reported in literature for several quinoline synthesis reactions in the gas phase. The gas-phase reaction of acetaldehyde with aniline gave higher yields than previously reported gas-phase quinoline synthesis reactions. Remarkably, both 4MeQ and 2MeQ were observed, with significant selectivity toward 4MeQ, and some quinoline was also produced. To the best of our knowledge, this is the first report of both 2- and 4-substituted quinolines as major reaction products. Interestingly, after some time on stream, 4MeQ was the predominant isomer. These observations rightly raise questions about the mechanism of formation of these positional isomers.

Yields were lower with the NH_4F-BEA* catalyst owing to decreased selectivity for quinolines. At 97% aniline conversion, a 71% combined yield of quinolines was obtained. The following observations arise from data shown in Table 1. Catalyst activated at 450 °C displayed high and stable conversions,