Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Catalysis 239 (2006) 362–368

JOURNAL OF CATALYSIS

www.elsevier.com/locate/jcat

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

Roald Brosius [a], David Gammon [b], Frederik Van Laar [a], Eric van Steen [c],
Bert Sels [a,*], Pierre Jacobs [a,*]

[a] *Centre for Surface Chemistry and Catalysis, Katholieke Universiteit Leuven, Kasteelpark Arenberg 23, 3001 Heverlee, Belgium*
[b] *Department of Chemistry, University of Cape Town, Rondebosch, 7701, South Africa*
[c] *Catalysis Research Unit, Department of Chemical Engineering, University of Cape Town, Rondebosch, 7701, South Africa*

Received 24 October 2005; revised 19 January 2006; accepted 22 February 2006

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.

Keywords: Vapour-phase synthesis; 2-methylquinoline; 4-methylquinoline; BEA* zeolite; Aniline; Acetaldehyde; Fluorination

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

---

[*] Corresponding authors.
E-mail addresses: bert.sels@agr.kuleuven.ac.be (B. Sels), pierre.jacobs@agr.kuleuven.ac.be (P. Jacobs).

doi:10.1016/j.jcat.2006.02.015

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,

Table 1
Aniline conversion, selectivities for Q, 2MeQ, 4MeQ and EA, yield of quinolines in selected experiments

Catalyst, $T_{pretreatment}$	$T_{reaction}$ (°C)	HOS (h)	C (%)[a] aniline	S (%)[b]				Yield[c] (%)
				2MeQ	4MeQ	Q	EA	
H-BEA*, 500 °C	450	2	76	24	27	10	/	46
		3	90	18	36	13	/	60
		4	94	20	45	12	/	72
		4.5	90	29	47	16	/	83
NH_4F-BEA*, 450 °C	428	0.5	66	23	48	5	4	50
		1	88	25	47	3	4	66
		2	93	28	42	2	4	67
		3	96	34	37	2	4	70
		4	97	37	32	2	5	69
		4.5	97	43	29	1	6	71
NH_4F-BEA*, 550 °C	450	1	62	27	55	6	1	55
		2.5	74	32	46	2	4	59
		3	78	39	41	2	6	64
		3.5	82	43	38	2	7	68
		4	81	43	33	1	11	62
		4.5	77	43	28	1	12	55
		5	72	46	27	1	13	53
		5.5	65	47	26	0	14	47

[a] C: conversion of aniline.

[b] S: product selectivity; 2MeQ: 2-methylquinoline, 4MeQ: 4-methylquinoline, Q: quinoline, EA: N-ethylaniline.

[c] Sum of yields of 2MeQ, 4MeQ and Q.

whereas catalyst activated at 550 °C showed only temporarily high activity. At the onset of the reaction, the selectivity for 4MeQ was twice that for 2MeQ regardless of catalyst pretreatment. After 4.5 HOS, 2MeQ became the predominant isomer. Note that the selectivity for EA also increased with time. The evolution of selectivity with time at 450 °C on NH_4F-BEA* catalyst activated at 550 °C is shown in Fig. 1. Because the H-BEA* catalyst does not display this peculiar behaviour, the evolution of product selectivities is probably related to gradually changing catalyst properties provoked by fluorination. Consequently, this catalyst was submitted to a more thorough investigation.

Solid-state ^{29}Si and ^{27}Al MAS NMR spectra were recorded. Fig. 2 shows ^{27}Al MAS NMR spectra of the BEA* zeolite after treatment with NH_4F (1), the NH_4F-BEA* catalyst after calcination at 550 °C and hydration (2), and the NH_4F-BEA* catalyst after activation at 550 °C and subsequent reaction at

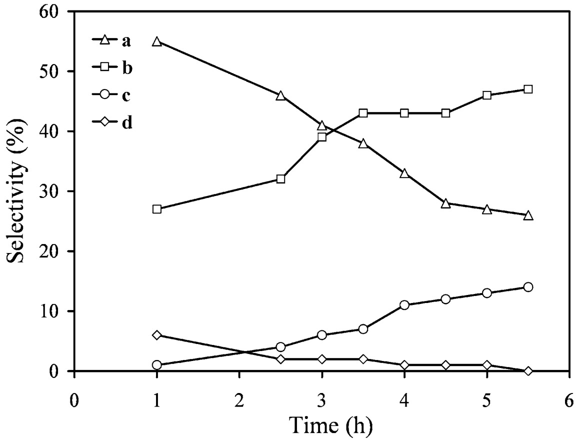

Fig. 1. Selectivity for 4MeQ (a), 2MeQ (b), EA (c) and Q (d) in the reaction of aniline with acetaldehyde over NH_4F-BEA* zeolite at 450 °C. The catalyst was activated at 550 °C.

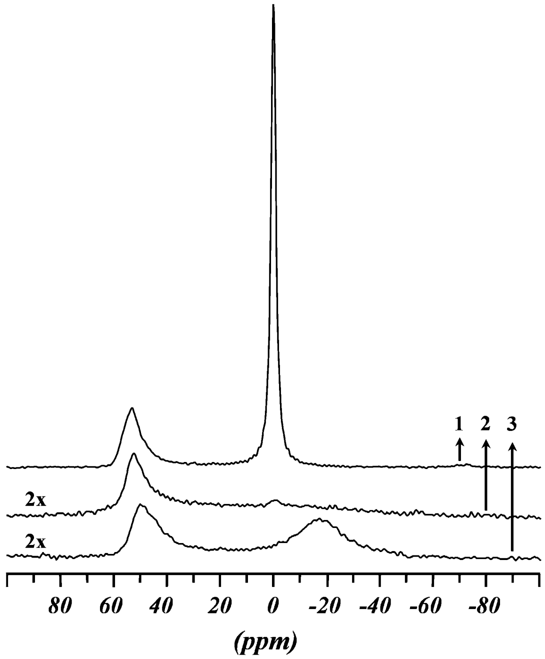

Fig. 2. ^{27}Al MAS NMR spectra of NH_4F-BEA* zeolite after impregnation with NH_4F and drying at 60 °C (1), after subsequent calcination at 550 °C and hydration (2) and after NH_4F treatment followed by activation at 550 °C and subsequent reaction at 450 °C (3).

Table 2
Overview of gas phase quinoline syntheses reported in literature

Catalyst	Reagents (rel. molar amounts)	$T_{reaction}$	Product	GHSV	Yield	Ref.
$SiO_2/Al_2O_3/F$ (84/15/1) wt%	Aniline:crotonaldehyde (1.5:1)	450 °C	4MeQ	200 h^{-1}[a]	11%[b]	[20]
Acid-treated montmorillonite	2-Ethylaniline:ethyleneglycol (1:2)	330 °C	2MeQ	3000 h^{-1}	41%[c]	[18]
Amorphous SiO_2/Al_2O_3	Ortho-toluidine:acetaldehyde + formaldehyde:H_2O (1:4:4)	470 °C	Q	1000 h^{-1}	54%[b]	[15]
$CuO–ZnO/Al_2O_3$	Aniline:glycerol (1:2)[d]	425 °C	Q	540 h^{-1}	65%[b]	[17]

[a] Estimated based on the value of 0.09 $mol_{aldehyde}\, L^{-1}_{catalyst}\, h^{-1}$ given by Uebel et al. [20].

[b] Calculation based on aniline base conversion.

[c] Calculation based on ethyleneglycol conversion.

[d] Air is used as carrier gas instead of nitrogen.

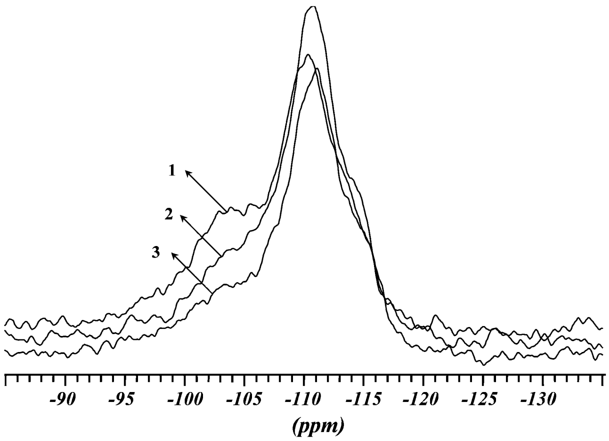

Fig. 3. ^{29}Si MAS NMR spectra of NH_4F-BEA* zeolite after treatment with NH_4F (1), after subsequent calcination at 550 °C and hydration (2) and after NH_4F treatment followed by activation at 550 °C and subsequent reaction at 450 °C (3).

Table 3
Aniline conversion, selectivities for Q, 2MeQ, 4MeQ and EA, yield of quinolines in selected experiments

Catalyst, $T_{\text{pretreatment}}$	T_{reaction} (°C)	HOS (h)	C (%)[a] aniline	S (%)[b] 2MeQ	4MeQ	Q	EA	Yield[c] (%)
BEA*-F, 550 °C	450	1	94	9	44	34	/	82
		2.5	98	16	43	18	/	75
		4.5	98	21	56	15	/	90
BEA*-F, 475 °C	450	1	18	4	18	19	/	7
		1.5	30	10	37	33	/	24[d]
		3	66	15	45	14	/	49[d]
		4	88	18	37	8	/	55[d]

[a] C: conversion of aniline.

[b] S: product selectivity; 2MeQ: 2-methylquinoline, 4MeQ: 4-methylquinoline, Q: quinoline, EA: N-ethylaniline.

[c] Sum of yields of 2MeQ, 4MeQ and Q.

[d] Other products included 2ProQ (2-propylquinoline) up to 8%, fully or partially hydrogenated products of the condensation of aniline with C2, C4, C6, etc., unsaturated aldehydes, α-anilino-butanaldehyde anil and β-anilino-butanaldehyde anil and traces of unidentified products.

450 °C (3). Comparison of ^{29}Si MAS NMR spectra shown in Fig. 3 reveals that the signal attributed to the $Q^4(1Al)$ species at approximately −103 ppm was lower for those samples exposed to calcination or to activation at 550 °C followed by reaction. Therefore, it can be concluded that dealumination occurred after pretreatment at high temperature. On NH_4F treatment of the BEA* zeolite, a very intense line due to sixfold-coordinated Al^{3+} species appeared at approximately 0 ppm. The spectrum of the sample calcined at 550 °C shows a peak due to tetrahedral Al^{3+} species on top of a very broad and flat band between 60 and −60 ppm, as demonstrated by the rise in the baseline. The line due to an Al^{VI} resonance almost completely disappeared. After subsequent prolonged exposure to the reaction gas at 450 °C, broad bands due to Al^{IV} and Al^{VI} resonances appeared with decreased chemical shift in the ^{27}Al MAS NMR spectrum.

Table 3 gives aniline conversion, product selectivities, and combined quinoline yields on BEA*-F catalyst. With BEA*-F activated at 550 °C, an aniline conversion of 98% with combined selectivities for 2MeQ, 4MeQ, and quinoline reaching 90% was obtained after 4.5 HOS at 450 °C. Activation at 475 °C resulted in a considerable delay in catalyst activity and decreased selectivity. With this catalyst, the ratio of 2MeQ/4MeQ was consistently <1. It is intriguing to note that in contrast to the NH_4F-treated BEA* zeolite, the selectivity for 4MeQ was stable on BEA*-F synthesized in the presence of fluoride. Zeolites were very poor in defect sites when the mineralizing species were fluoride ions, whereas high-silica zeolites made in basic medium with hydroxyl ions displayed a substantial number of framework defects. It is known that $SiO_{4/2}F^-$ units balance the positive charge of organic structure-directing agents, whereas in zeolites synthesized in basic medium, hydroxyl groups are structurally integrated to balance the positive charge [21]. Calcination removes the organic molecules and fluoride anions occluded in the solids [23,24]. In contrast, postsynthesis treatment with NH_4F may give rise to the formation of Si–F and/or Al–F linkages during activation of the zeolite [26,27].

4. Discussion

4.1. The effect of fluorination

The NMR spectra of the NH_4F-BEA* catalyst show that exposure to the reaction gas mixture at 450 °C after activation at 550 °C led to the formation of extra-framework fluorinated aluminium compounds as well as tetrahedral Al^{3+} species presumably containing Al–F bonds, as evidenced by the decreased chemical shift of both the tetrahedral and the octahedral Al^{3+} species due to the increased proximity of the F atom. The effects of fluorination have received ample attention in the literature. On reaction of molecular fluorine with H-ZSM-5 at room temperature, nonframework fluorinated species weakly attached to the lattice are formed [25]. In our case, on NH_4F impregnation, octahedral Al^{3+} species were formed. On H-ZSM-5, NH_4F impregnation followed by calcination at temperatures above 500 °C leads to the formation of Si–F bonds and to dealumination and formation of extra-framework aluminum species [26,28]. There is a general concensus that fluorination provokes dealumination of the zeolite framework regardless of the fluorination method used [29]. Furthermore, fluorination may lead to decreased pore volume and specific surface area [30]. H-BEA* zeolite modified by aqueous solutions of HF exhibits an increased ratio of Lewis acidity to Brønsted acidity and of strong sites to weak sites but with diminished total acidity [30]. On alumina, the number of Lewis acid sites increases significantly with fluorine addition [31]. Depending on the degree of hydration and the fluorine content, various species, such as aluminium hydroxyfluorides or hydrated aluminium trifluoride, can be found on the catalyst surface.

There are a number of plausible explanations for the evolution of the selectivities for 4MeQ and 2MeQ over NH_4F-BEA*. The first of these assumes that the observations are related to the catalyst acidity. Over a fluor-containing amorphous aluminosilicate catalyst, the gas-phase reaction of aniline with crotonaldehyde resulted in 4MeQ at 450 °C [20]. The presence of water was not mentioned, and we thus assume that Lewis acid sites prevailed on this catalyst. It may then be suggested that Lewis acidity and the formation of 4MeQ are somehow related. Given the considerable amount of water in our experiments, it seems unlikely that a significant amount of coordinatively unsaturated Al^{3+} species exhibiting Lewis acidity remained. The acidity associated with extra-framework fluorinated aluminium compounds in the presence of water was probably of the Brønsted type. Perhaps the decreasing selectivity for 4MeQ in the experiment with NH_4F-BEA* catalyst could be due to depletion of the appropriate Lewis acid sites as a consequence of catalyst hydration and dealumination.

Another explanation assumes an important role for the structural parameters of the zeolite catalyst rather than the acidity. Shape selectivity may favour one isomer over the other. Gradual dealumination of the NH_4F-BEA* catalyst may lead to partial pore blocking or to micropore size restrictions due to extra-lattice aluminium compounds. The less bulky isomer 2MeQ then would be favoured over 4MeQ. This can be observed after 4.5 HOS over the NH_4F-BEA* catalyst. BEA*-F zeolite catalyst, on the other hand, presumably has very few lattice defects and displays high and stable selectivity for 4MeQ formation. In this case the zeolite would not impose restrictions on the synthesis of the more bulky isomer 4MeQ. We prefer this second explanation, which is supported by the fact that H-BEA* and BEA*-F catalysts displayed similar product selectivities (compare Table 1, line 4 and Table 3, line 3). In conclusion, we believe that shape selectivity caused by pore size restriction determines the distribution of products over the NH_4F-BEA* catalyst.

4.2. The reaction mechanism

Fig. 4 provides a tentative overview of plausible reaction pathways leading to 2MeQ and 4MeQ. In pathways 1 and 2, an imine (Schiff base) was formed from aniline and acetaldehyde, whereas in pathways 3 and 4, aniline reacted with crotonaldehyde, the product of aldol condensation of two acetaldehyde units. In pathway 3, an imine was formed, whereas in pathway 4, conjugate or Michael-type addition of aniline to crotonaldehyde occurred. In this section we present evidence in favour of and against these propositions.

At first sight, observations reported in the literature seem to suggest that a higher reaction temperature gives preference to 4MeQ formation [20], whereas lower temperatures favour 2MeQ [18]. This seems to be in line with the heats of formation of 4MeQ (262.3 kJ mol^{-1}) and 2MeQ (93.6 kJ mol^{-1}) [18]. In several of our experiments, the temperature was lowered to 350 °C. Besides low aniline conversions, increased selectivity for 2MeQ compared with 4MeQ was indeed observed. At the same time, the byproduct EA was also found in large quantities at 350 °C. This suggestion finds confirmation in Fig. 1, which shows that at 450 °C over NH_4F-BEA*, the selectivity for EA increased as 4MeQ decreased with HOS. Therefore, it can be suggested that AA, giving EA after hydrogen transfer, is a reaction intermediate rather than a mere byproduct. This casts doubt on the assumption that the α,β-unsaturated aldehyde is a reaction intermediate in the formation of 4MeQ. Forrest et al. demonstrated the viability of a mechanism for the liquid-phase synthesis of 2MeQ from aniline and acetaldehyde that does not involve formation of the α,β-unsaturated aldehyde

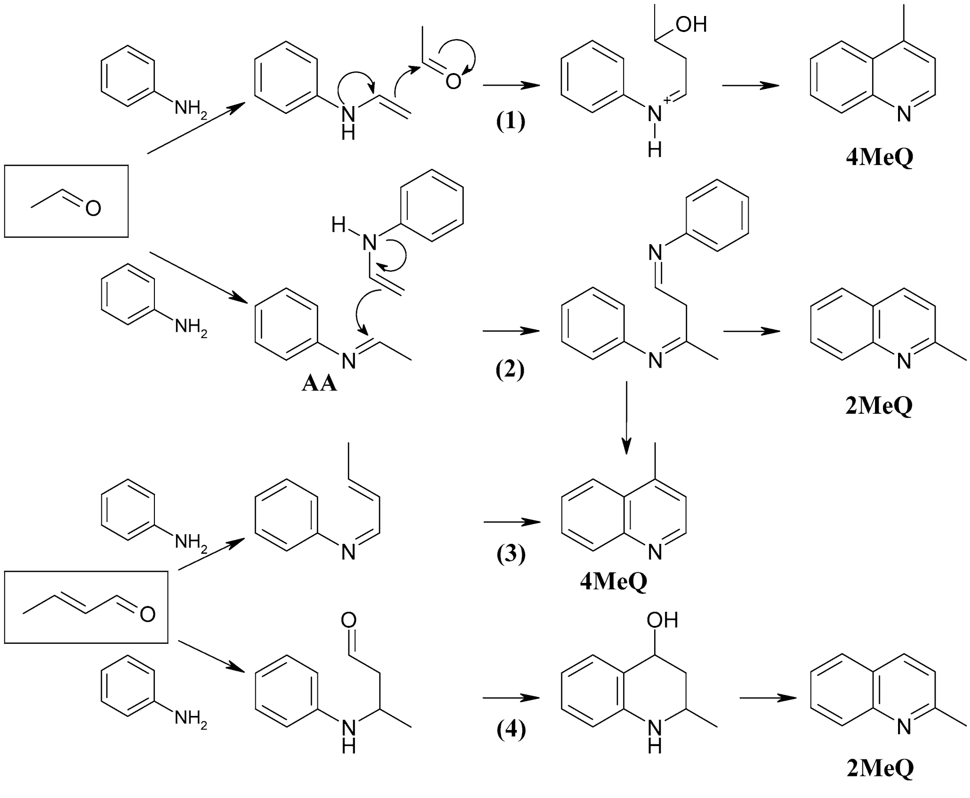

Fig. 4. Schematic overview of reaction pathways leading to formation of 2MeQ or 4MeQ.

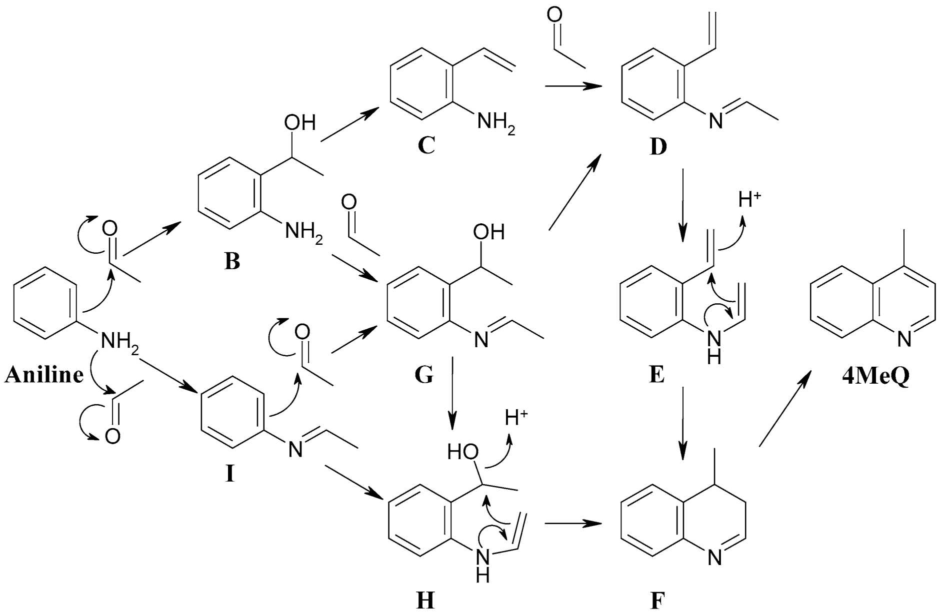

Fig. 5. Schematic representation of the ortho-alkylation route to formation of 4MeQ.

first (Fig. 4, pathway 2) [32]. The gas-phase aniline–acrolein reaction gave poor yields [15]. In addition, McAteer et al. reported that the aniline–crotonaldehyde reaction yielded an excess of 4MeQ over 2MeQ at 450 °C. In a recent study of the reaction of *o*-toluidine (*o*TOL) with ^{13}C-enriched formaldehyde and acetaldehyde, the ^{13}C enhancement in individual positions of the heterocyclic ring of resulting quinoline was analysed by ^{1}H and ^{13}C NMR spectroscopy, and it was found that ^{13}C was incorporated almost exclusively in the C-2 position, not in the C-4 position, of the heterocyclic ring. This finding suggests that a mechanism involving condensation of formaldehyde with *o*TOL to form the Schiff base methanimine intermediate that reacted further with acetaldehyde was favoured over Michael addition of *o*TOL to acrolein (arising from aldol condensation of acetaldehyde and formaldehyde), because the former resulted in incorporation of ^{13}C at the C-2 position. Therefore, Schiff base condensation of acrolein with *o*TOL is not in keeping with the observed ^{13}C incorporation measurements [34]. These results are consistent with our observation that the imine of aniline and acetaldehyde, AA, is possibly an intermediate in the formation of 4MeQ. Therefore, based on the correlation of the selectivity for 4MeQ and EA in the reaction over NH_4F-BEA* catalyst and on the above evidence, we propose that 4MeQ is formed according to pathway 1 rather than pathway 3 in Fig. 4. AA undergoes a hydride shift to form the corresponding enamine, which subsequently reacts with acetaldehyde followed by intramolecular electrophilic aromatic substitution, resulting in ring closure. Thus, 4MeQ is synthesized in a stepwise manner.

The alternative route involving the Schiff base dimerisation reaction as shown in pathway 2 proceeds via a very bulky intermediate that can in principle give rise to both 2MeQ and 4MeQ. However, it is unlikely to be a major pathway in the confined space of a microporous shape-selective catalyst, such as NH_4F-BEA*, after 4.5 h, where formation of 2MeQ over 4MeQ is favoured. Thus, formation of 2MeQ seems to arise from the Michael addition of aniline to the α,β-unsaturated aldehyde crotonaldehyde, followed by a ring-closing electrophilic aromatic substitution (pathway 4).

If the ortho-alkylation route, touched on in Section 1, is to be taken at all seriously, one might envisage that 4-methylquinoline is formed (as shown in Fig. 5) through ortho-alkylation of aniline or its derived imine (**I**) with acetaldehyde to give the hydroxyethylated derivatives (**B** and **G**), followed by sequences of dehydrations, H-shifts, and intramolecular acid-catalysed reactions. There is no precedent for this mechanism in the literature, however. This mechanism would require a fairly strong Lewis acid site, the presence of which has not been convincingly demonstrated in BEA* zeolite or NH_4F-BEA*, particularly not in wet conditions. Therefore, it makes sense to not overestimate the importance of this pathway.

In conclusion, it seems that the higher temperatures favour the imine route with stepwise formation of 4MeQ, whereas the lower temperature route involves Michael addition to the α,β-unsaturated aldehyde, leading to 2MeQ preferentially.

5. Conclusion

BEA* zeolite displayed high activity for the synthesis of both 2MeQ and 4MeQ from aniline and acetaldehyde. A 90% combined yield of 2MeQ, 4MeQ, and quinoline was obtained with BEA*-F zeolite catalyst synthesized in fluoride medium. The gas-phase reaction of aniline with acetaldehyde produced 4MeQ, as well as considerable amounts of 2MeQ, which had not been reported previously. Postsynthesis fluorination of the BEA* zeolite provoked dealumination during the quinoline synthesis reaction. The catalyst changes were reflected in a transient product distribution with opposite trends for 4MeQ on the one hand and 2MeQ and *N*-ethylaniline on the other hand. We propose that the dealumination leads to narrowing of the micropores, allowing preferential formation of the less bulky isomer 2MeQ. High temperatures favour formation of 4MeQ in a stepwise manner starting with formation of the imine from aniline and acetaldehyde. Lower temperatures favour the Michael addition of aniline to crotonaldehyde, resulting in 2MeQ formation.

Acknowledgments

This work is supported by the National Research Foundation of South Africa and the Flemish government (Bilateral Scientific Cooperation BIL 04/53). B.S. and P.A.J. thank the Belgian government for financial support (IUAP project on supramolecular chemistry and catalysis).

References

[1] Ullman's Encyclopedia of Industrial Chemistry, sixth ed., Wiley–VCH, New York, 1999, Electronic Release.
[2] R.H.F. Manske, M. Kulka, in: R. Adams (Ed.), Organic Reactions, vol. 7, Wiley, New York, 1953, p. 59.
[3] Z.H. Skraup, Ber. Dtsch. Chem. Ges. 13 (1880) 2086.
[4] O. Döbner, W. von Miller, Ber. Dtsch. Chem. Ges. 14 (1881) 2816.
[5] R.G. Gould, W.A. Jacobs, J. Am. Chem. Soc. 61 (1939) 2890.
[6] Y. Watanabe, N. Suzuki, Y. Ohsuji, Tetrahedron Lett. 22 (1981) 2667.
[7] Y. Watanabe, N. Suzuki, Y. Tsuji, S.C. Shim, T. Mitsudo, Bull. Chem. Soc. Jpn. 55 (1982) 1116.
[8] Y. Watanabe, Y. Tsuji, J. Shida, Bull. Chem. Soc. Jpn. 57 (1984) 435.
[9] Y. Watanabe, K. Takatsuki, S.C. Shim, T. Mitsudo, Y. Takegami, Bull. Chem. Soc. Jpn. 51 (1978) 3397.
[10] J. Jacob, W.D. Jones, J. Org. Chem. 68 (2003) 3563.
[11] C.S. Cho, B.H. Oh, J.S. Kim, T.-J. Kim, S.C. Shim, Chem. Commun. (2000) 1885.
[12] C.S. Cho, B.H. Oh, D.T. Kim, T.-J. Kim, S.C. Shim, Bull. Korean Chem. Soc. 24 (2003) 1026.
[13] S. Kobayashi, H. Ishitani, S. Nagayama, Chem. Lett. (1995) 423.
[14] H. Ishitani, S. Kobayashi, Tetrahedron Lett. 37 (1996) 7357.
[15] C.H. McAteer, R.D. Davis, J.R. Calvin, World patent WO9703051, 1997.
[16] P.R. Reddy, K.V. Subba Rao, M. Subrahmanyam, Catal. Lett. 56 (1998) 155.
[17] B.M. Reddy, I. Ganesh, J. Mol. Catal. A 151 (2000) 289.
[18] M. Campanati, P. Savini, A. Tagliani, A. Vaccari, Catal. Lett. 47 (1997) 247.
[19] M. Campanati, A. Vaccari, O. Piccolo, Catal. Today 60 (2000) 289.
[20] H.J. Uebel, K.K. Moll, M. Mühlstädt, J. Prakt. Chem. 312 (1970) 263.
[21] H. Koller, A. Wölker, L.A. Villaescusa, M.J. Díaz-Cabañas, S. Valencia, M.A. Camblor, J. Am. Chem. Soc. 121 (1999) 3368.
[22] T. Blasco, M.A. Camblor, A. Corma, P. Esteve, J.M. Guil, A. Martinez, J.A. Perdigón-Melón, S. Valencia, J. Phys. Chem. B 102 (1998) 75.
[23] M.A. Camblor, A. Corma, S. Valencia, J. Matter. Chem. 8 (1998) 2137.
[24] H. Koller, A. Wölker, H. Eckert, C. Panz, P. Behrens, Angew. Chem. Int. Ed. Engl. 36 (1997) 2823.
[25] N.A. Sánchez, J.M. Saniger, J.-B. d'Espinose de la Caillerie, A.L. Blumenfeld, J.J. Fripiat, Microporous Mesoporous Mater. 50 (2001) 41.
[26] R. Le Van Mao, T.S. Le, M. Fairbairn, A. Muntasar, S. Xiao, G. Denes, Appl. Catal. A 185 (1999) 41.
[27] R.B. Borade, A. Clearfield, J. Chem. Soc., Faraday Trans. 91 (1995) 539.
[28] S.K. Pur, R.G. Bryant, Zeolites 16 (1996) 118.
[29] A.G. Panov, V. Gruver, J.J. Fripiat, J. Catal. 168 (1997) 321.
[30] M. Han, C. Xu, J. Lin, Y. Liang, E. Roduner, Catal. Lett. 86 (2003) 81.
[31] M. Moreno, A. Rosas, J. Alcaraz, M. Hernández, S. Toppi, P. Da Costa, Appl. Catal. A 251 (2003) 369.
[32] T.P. Forrest, G.A. Dauphinee, W.F. Miller, Can. J. Chem. 47 (1969) 2121.
[33] T. Sugasawa, T. Toyoda, M. Adachi, K. Sasakura, J. Am. Chem. Soc. 100 (1978) 4842.
[34] J.R. Calvin, R.D. Davis, C.H. McAteer, Appl. Catal. A 285 (2005) 1.