

Faujasite catalysis of aromatic nitrations with dinitrogen pentoxide. The effect of aluminium content on catalytic activity and regioselectivity. The nitration of pyrazole †

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Robert P. Claridge,^a N. Llewellyn Lancaster,^b Ross W. Millar,^a Roy B. Moodie ^{*b} and John P. B. Sandall^b

^a Defence Evaluation and Research Agency, Fort Halstead, Sevenoaks, Kent, UK TN14 7BP

^b School of Chemistry, University of Exeter, Exeter, UK EX4 4QD

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The reaction of 1-chloro-2-nitrobenzene with dinitrogen pentoxide in dichloromethane catalysed by H-faujasite zeolites F-712, F-720, F-780 and F-901, giving 1-chloro-2,4-dinitro- and 1-chloro-2,6-dinitrobenzene in approximately 30:1 ratio, is a kinetically first-order process. First-order rate constants are independent of the concentration of N_2O_5 and proportional to the mass of catalyst used. Specific rate constants, obtained by dividing the first-order rate constant by the mass of faujasite, are constant for a given faujasite. Amongst the faujasites, they increase in approximate proportion to the aluminium content. A mechanism is proposed in which the protons in the faujasite, near aluminium in the faujasite framework, are replaced by nitronium ions derived from N_2O_5 in a fast pre-equilibrium process. This produces active sites for transfer of nitronium ion from faujasite to aromatic in the rate-determining step. The similar reactions of 2-nitrotoluene, too fast for kinetic study, reveal that the ratio of 2,4- to 2,6-dinitrotoluene in the product increases with the aluminium content of the faujasite.

Nitration of nitrobenzene is also catalysed by faujasite. Relative reactivities of nitrobenzene, 1-chloro-2-nitro- and 1-chloro-4-nitrobenzene are compared to those found in mixed-acid nitration.

Pyrazole can be nitrated readily with N_2O_5 over faujasites, yielding 1,4-dinitropyrazole in 80% yield under mild conditions.

Introduction

The use of zeolites in aromatic nitrations is a subject of increasing interest, particularly with regard to unusual regioselectivities.^{1,2} We have been investigating the kinetics and mechanism of aromatic nitrations with N_2O_5 in dichloromethane which are strongly catalysed by certain zeolites, and in particular by H-faujasites.³ This reaction is kinetically first-order, and the observed rate constant is proportional to the mass of faujasite used but independent of the concentration of N_2O_5 (provided this is present in at least two-fold excess).³ In this paper we explore the relative effectiveness of faujasites which differ in their aluminium content. Specific rate constants (first-order rate constants divided by the mass of zeolite used) increase with aluminium content and this provides further support for, and insight into, a mechanism previously outlined.³

The conversion of pyrazole to 1,4-dinitropyrazole, using ammonium nitrate in trifluoroacetic anhydride and trifluoroacetic acid, has been reported,⁴ but nitration by N_2O_5 (generated *in situ* from nitrogen dioxide and ozone) has been found to give 1-nitropyrazole only.⁵ We now report that the faujasite-catalysed reaction with N_2O_5 yields 1-nitropyrazole immediately which is slowly converted to 1,4-dinitropyrazole, in a reaction which shows an induction period. Starting with 1-nitropyrazole, however, the formation of 1,4-dinitropyrazole is a first-order process with no induction period.

Results

The kinetics of nitration of 1-chloro-2-nitrobenzene catalysed by H-faujasites F-712, -720, -780, and -901

These faujasites were dried at 350 °C under vacuum before use and handled in a dry glovebox as previously described.³ Prior to applying this procedure, F-712, which unlike the others was supplied in the ammonium form, was converted to the proton form by heating⁶ to 500 °C for 72 hours.

The results are in Table 1. For consistency in the comparison, the same analytical procedure and kinetic analysis were applied in all runs quoted. Some of the results for F-720 given previously³ were not obtained by the same procedures and are not included here. The results confirm that the reactions are kinetically close to first-order (a typical run is shown in Fig. 1) and zeroth order in N_2O_5 , with specific rate constants k_z (first-order rate constants divided by zeolite mass) being approximately constant for each zeolite. Average values of k_z for each zeolite are in Table 1.

The reactions all produced 1-chloro-2,4-dinitrobenzene as the major product, with small amounts of 1-chloro-2,6-dinitrobenzene. The ratio of the former to the latter was approximately 30:1. There was no evident trend in this ratio with the aluminium content of the zeolite but, because of the small amount of 1-chloro-2,6-dinitrobenzene formed, the ratio could not be measured with precision.

The nitration of 2-nitrotoluene

The reaction of 2-nitrotoluene with N_2O_5 catalysed by H-faujasites, too fast to follow kinetically, was investigated to

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Table 1 First-order rate constants k and specific constants $k_z = k/z$ in the reaction of 1-chloro-2-nitrobenzene (initial concentration 0.10–0.13 mol dm⁻³) with N₂O₅ at 0 °C in dichloromethane (6–7 cm³) in the presence of a mass z of faujasite

[N ₂ O ₅]/ mol dm ⁻³	z /mg	10 ³ k / s ⁻¹ ± 5%	10 ³ k_z / s ⁻¹ g ⁻¹	Mean value of 10 ³ k_z /s ⁻¹ g ⁻¹
F-712				
0.262	58	1.13	20	24
0.265	100	2.35	24	
0.267	200	4.20	21	
0.278	235	7.02	30	
0.272	313	8.60	27	
F-720				
0.229	144	1.70	12	13
0.353	149	1.80	12	
0.437	151	2.22	15	
0.255	320	4.28	13	
F-780				
0.242	57	0.232	4.1	4.1
0.258	111	0.550	5.0	
0.255	215	0.908	4.2	
0.255	327	1.44	4.4	
0.242	438	1.26	2.9	
F-901				
0.247	241	0.388	1.6	1.6
0.282	320	0.548	1.7	
0.308	467	0.683	1.5	

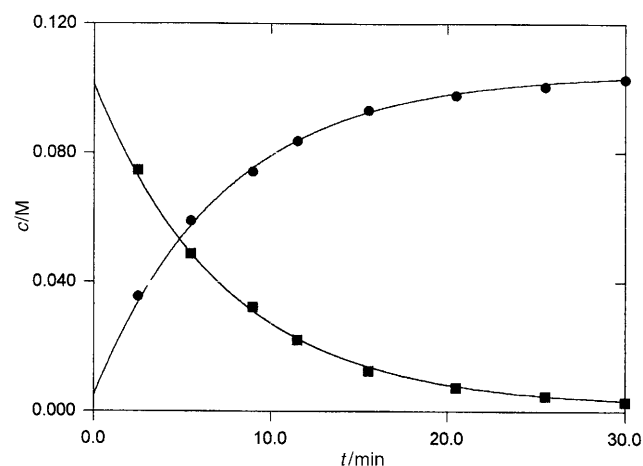


Fig. 1 Concentration c against time t in the nitration of 1-chloro-2-nitrobenzene by N₂O₅ (0.44 mol dm⁻³) in the presence of F-720 (0.151 mg) in dichloromethane (6 cm³) at 0 °C. Squares: 1-chloro-2-nitrobenzene. Circles: 2,4-dinitrochlorobenzene plus 2,6-dinitrochlorobenzene, of which >95% is the former. Curves are computer-fitted first-order curves.

determine the effect of aluminium content of the zeolite on the regioselectivity of the nitration. In this case, there was a noticeable decrease in the 2,4-/2,6-dinitrotoluene ratio with decrease in the aluminium content of the faujasite; results are in Table 2.

The nitration of nitrobenzene

This was investigated to compare its reactivity with those of 1-chloro-2-nitrobenzene (Table 1) and 1-chloro-4-nitrobenzene.³ Specific rate constants are in Table 3. The product ratios were determined by NMR and were closely similar to those found in mixed-acid nitration.

The nitration of pyrazole

The reaction of pyrazole (**1**) with N₂O₅ in the presence of F-720 gave a good yield of 1-nitropyrazole (**2**) immediately. This was

Table 2 Yields of 2,4-dinitrotoluene (24DNT) and 2,6-dinitrotoluene (26DNT) following nitration of 2-nitrotoluene (0.125 mol dm⁻³) by N₂O₅ (0.23–0.25 mol dm⁻³) in 6 cm³ dichloromethane over faujasite (0.10–0.11 g)

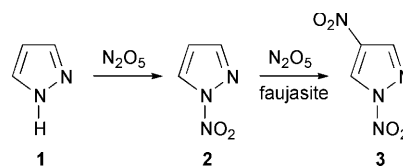
H-Faujasite	Yield (%)			R^a
	Overall	24DNT	26DNT	
F-712	92	77	15	5.2
F-720	89	72	17	4.3
F-780	91	69	22	3.2
F-901	92	69	23	3.0

^a Ratio 24DNT:26DNT.

Table 3 First-order rate constants k and specific constants k_z ($k_z = k/z$) in the reaction of nitrobenzene (initial concentration 0.11–0.12 mol dm⁻³) with N₂O₅ (initial concentration 0.23–0.24 mol dm⁻³) at 0 °C in dichloromethane (7 cm³) in the presence of a mass z of F-720

z /mg	10 ³ k / s ⁻¹ ± 5%	10 ³ k_z / s ⁻¹ g ⁻¹	Mean value of 10 ³ k_z /s ⁻¹ g ⁻¹	Yield (%)	$o:m:p$
50	0.51	10		90	^a
103	1.13	11		84	6:92:2
147	1.13	8	9	^a	^a
186	1.60	9		^a	^a
252	1.64	7		85	^a

^a Not determined.



Scheme 1

converted slowly to 1,4-dinitropyrazole (**3**) (Scheme 1) in a reaction showing a marked induction period (Fig. 2, full lines and symbols). Use of F-780 led again to complete disappearance of pyrazole and a good yield of 1-nitropyrazole within 5 minutes, but the further reaction to give **3** was very much slower than with F-720. There was a 4.5% yield (based on the initial pyrazole) of **3** formed after 30 minutes, but 25% after 60 minutes, again indicative of an induction period in the second stage of the dinitration (Scheme 1).

The nitration of 1-nitropyrazole

The observation of an induction period in the conversion **2**→**3** using F-720 as the catalyst when **1** was used initially (Fig. 2, full lines and closed symbols) led us to examine the reaction of **2** prepared independently (Fig. 2, pecked line and open circles). The contrast was remarkable. Within 5 minutes, **3** (not entirely stable under the conditions, see Fig. 2) was formed in 90% yield and no **2** remained.

When **1** is the starting material, a molar equivalent of nitric acid is produced along with **2** in the first step. To investigate whether this might account for the slowness and apparent induction period in the second step, the reaction of **2** with nitric acid added initially was studied. However the rate profile was almost identical (see Fig. 2 and legend) to that obtained when nitric acid was not added. Thus, in the dinitration of **1**, the nitric acid produced along with **2** in the first step does not explain the slowness, nor the apparent induction period, in the second step.

Using F-780 as the catalyst, the reaction **2**→**3** was much slower. Good first-order kinetics were observed. Specific rate constants, and yields, are in Table 4.

Table 4 First-order rate constants k and specific constants k_z ($k_z = k/z$) in the reaction of 1-nitropyrazole (**2**) (initial concentration 0.12 mol dm⁻³) with N₂O₅ (initial concentration 0.30–0.37 mol dm⁻³) at 0 °C in dichloromethane (6 cm³) in the presence of a mass z of F-780

z/mg	$10^3 k/\text{s}^{-1} \pm 5\%$	$10^3 k_z/\text{s}^{-1} \text{g}^{-1}$	Mean value of $10^3 k_z/\text{s}^{-1} \text{g}^{-1}$	Conversion (%) ^a	Yield (%) ^b
198	0.451	2.3		42	86
358	0.928	2.6	2.2	63	85
485	0.864	1.8		60	81

^a Yield of **3** at 60 minutes. ^b Yield of **3** and unreacted **2** at 60 minutes.

Table 5 The relation between the aluminium content of the faujasite, expressed as x in H _{x} Al _{x} Si_{192- x} O₃₈₄, and the mean specific rate constant for the faujasite-catalysed nitration of 1-chloro-2-nitrobenzene by N₂O₅ in dichloromethane at 0 °C

	x	$10^3 k_z/\text{s}^{-1} \text{g}^{-1}$
F-712	25	24
F-720	12	13
F-780	4.2	4.1
F-901	3.7	1.6

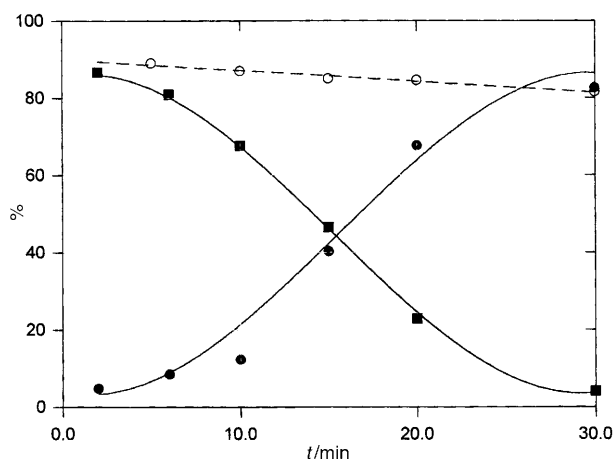


Fig. 2 Full lines: Yields (% of initial pyrazole (**1**)) of 1-nitropyrazole (**2**) (squares) and 1,4-dinitropyrazole (**3**) (full circles) as a function of time t in the nitration of **1** (0.124 M) by N₂O₅ (0.482 M) in the presence of F-720 (0.135 g) in dichloromethane (6 cm³) at 0 °C. No unreacted **1** could be detected even at the first point. Lines are arbitrary smooth curves through the points. Pecked line: Yields (% of initial **2**) of **3** (open circles) as a function of time t in the nitration of **2** (0.118 M) by N₂O₅ (0.288 M) in the presence of F-720 (0.135 g) in dichloromethane (6 cm³) at 0 °C. No unreacted **2** could be detected even at the first point. A reaction under closely similar conditions but with nitric acid (0.178 M) added initially gave an almost identical rate profile (not shown).

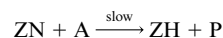
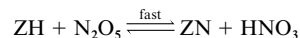
Discussion

Effects of aluminium content on reactivity and regioselectivity. The mechanism of faujasite-catalysed N₂O₅ nitration

The results in Table 1 show that in the nitration of 1-chloro-2-nitrobenzene, the specific rate constant k_z varies with the aluminium content of the faujasite. The faujasites used here, assumed to be completely in their proton forms and freed from water by the drying procedure, have the formula H _{x} Al _{x} Si_{192- x} O₃₈₄. Values of x in this formula, determined by XRF, are compared with the mean values of k_z in Table 5. The results show that the specific rate constant increases with the aluminium content of the faujasite, and is approximately proportional to it. These results should be treated with caution since they relate to a reaction which is heterogeneous and where factors such as the stirring speed could be important. However (a) separate investigations revealed little effect of changing the stirring speed, except that a completely unstirred solution

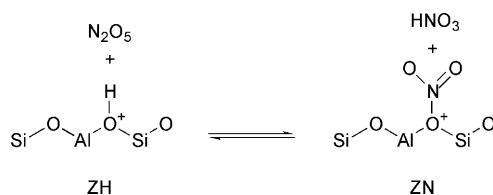
reacted more slowly, and (b) the reactions with the various faujasites were performed under identical conditions and it is unlikely that the systematic trend evident in Table 5 could have arisen fortuitously.

In protonic faujasites, oxygen atoms linked to aluminium carry the protons. These are the acid sites. It seems reasonable to conclude that the protons at the acid sites are replaced by nitronium ions to create the active sites. As previously postulated,³ the first-order nature of the reaction, the proportionality of the first-order rate constant to the mass of zeolite used, and the independence of the same quantity on the concentration of N₂O₅, all point to a mechanism of the type outlined in Scheme 2.



Scheme 2

In this scheme A represents the aromatic reactant and P the aromatic product(s). The potential sites on the zeolite for reaction are called ZH and these are converted to an active nitrating form ZN by reaction with N₂O₅. With the first step a fast pre-equilibrium, the equilibrium position lying well to the right, and the second step slow and rate-determining, the disappearance of aromatic substrate and the appearance of aromatic product would follow a first-order rate law, with a rate constant independent of the concentration of N₂O₅ but proportional to the mass of zeolite used, as observed. If now the sites ZH are identified with protonic sites next to aluminium, and the sites ZN with the same locations but with protons replaced by nitronium ions (Scheme 3), the near-proportionality (Table 5) of the



Scheme 3

catalytic activity to the aluminium content, *i.e.* to the number of acid sites, is explained.

For the range of faujasites examined, (Si:Al > 5.5) it is likely that all the protonic sites ZH are of the “strongly acidic” type.⁷ It is therefore likely that the ZN sites provide rather readily an incipient nitronium ion for transfer to the aromatic in the nitration process.

It is noteworthy that the relative reactivities of 1-chloro-4-nitrobenzene,³ nitrobenzene (Table 3) and 1-chloro-2-nitrobenzene (Table 1), as measured by the value of k_z with F-720 catalyst, are in the approximate ratio of 1:19:25, not too dissimilar from normal mixed-acid nitronium ion nitration where the ratio is 1:8:32.⁸

The mechanism outlined in Schemes 2 and 3 therefore accounts for most of the observations. It is as yet incomplete because the reaction is known to be inhibited by the aromatic product.³

An effect of aluminium content on regioselectivity has been demonstrated in one case. The data in Table 2 show that in faujasite–N₂O₅ nitrations of 2-nitrotoluene selectivity in favour of 2,4- rather than 2,6-dinitrotoluene formation increases with increasing aluminium content.

The nitration of aromatic heterocyclic compounds. Pyrazole and 1-nitropyrazole

We wished to extend the study of the efficacy of the nitrating system to heterocyclic aromatics. Our initial studies with quinoline, not reported here, gave only immediate and complete

Table 6 Molar ratio, SiO₂:Al₂O₃, in the faujasites used as determined in three ways

	Z ^a	SEM ^a	XRF ^{a,b}
F-712	11.5	15.5	13.2
F-720	30.8	28.6	30.8
F-780	83.4	68.1	88.4
F-901	>80	^c	103.2

^a See Experimental for details of the methods used. ^b Figures used to determine the values of x in H _{x} Al _{x} Si_{192- x} O₃₈₄ quoted in Table 5. ^c Poor reproducibility precluded a reliable figure being obtained.

N-nitration. The product (1-nitroquinolinium nitrate), being ionic, may well be unsuitable for further zeolite-catalysed nitration. No such problem should attend the nitration of five-membered ring nitrogen heteroaromatics. Pyrrole is much too reactive to be suitable for this aggressive nitrating system so pyrazole (**1**) was selected for investigation. In the absence of the solid catalyst, pyrazole with N₂O₅ is reported to give only *N*-nitration,⁵ the first step in Scheme 1. We find that faujasites are effective catalysts to convert the first-formed 1-nitropyrazole (**2**) into 1,4-dinitropyrazole (**3**).

The kinetics of the reaction **2**→**3**, studied independently using F-780 as the catalyst, have the same form as found for the aromatic nitrations described above. The reactivity of **2** is comparable to that of 1-chloro-2-nitrobenzene (Tables 1 and 4). (This relative reactivity, however, applies only to the F-780-catalysed reaction described here. The F-720-catalysed reaction was too fast to study kinetically (Fig. 2). Under acidic conditions, protonation of the pyrazole severely reduces its reactivity.⁹)

The contrast between the kinetics of **2**→**3** when **1** or **2** is used initially (Fig. 2) remains unexplained. We have demonstrated that the nitric acid produced in the first nitration step is not the cause of this difference. In the absence of an alternative explanation we speculate that the first nitration step **1**→**2**, which is not quantitative, is accompanied by a minor side reaction which temporarily poisons the catalytic sites.

Conclusions

The mechanism previously outlined³ for the faujasite-catalysed nitration of deactivated aromatics by N₂O₅ is supported by the present results, which further indicate that the active sites in the faujasite are close to aluminium atoms and that reaction occurs by transfer of nitronium ion from these sites to the aromatic. The reaction can be extended to deactivated five-membered ring aromatic heterocycles.

Experimental

Materials

These were mostly as described.³

Pyrazole and 1-nitropyrazole were used as supplied.

Drying of faujasites

These were dried exactly as described previously for the drying of zeolites,³ except that, with faujasite 712, which was supplied in the ammonium form, de-ammoniation was effected by heating the sample in a silica boat at 500 °C for 72 hours prior to applying the procedure.

Aluminium content of faujasites

Values for the molar ratio, SiO₂:Al₂O₃, were obtained in three ways: from the supplier's (Zeolyst) literature (Z), from scanning

electron microscopy (SEM), and by X-ray fluorescence (XRF). Values are in Table 6. We thank the Earth Resources Centre at the University of Exeter for the SEM and XRF measurements. The XRF values, being the only complete set, were used to derive the values of x in H _{x} Al _{x} Si_{192- x} O₃₈₄ used in Table 5.

4-Nitropyrazole

This was prepared as described.¹⁰

1,4-Dinitropyrazole

This was prepared in a similar manner to that described.⁵ In a dry atmosphere glove box was placed a flask containing 4-nitropyrazole (0.1 g, 0.88 mmol) and a magnetic follower. To this was added N₂O₅ (0.226 g, 2.09 mmol) and dichloromethane (5 cm³) and the mixture was stirred at room temperature for 60 min. Rotary evaporation left a yellow oil which crystallised on standing. δ_{H} (300 MHz, CDCl₃) 9.06 (1H, s, CH), 8.20 (1H, s, CH); m/z M⁺: 158.00791 (expected 158.00761). Column chromatography caused the product to decompose by loss of the *N*-nitro function, giving 4-nitropyrazole in 85% yield.

Kinetic and product studies of the nitration of 2-chloronitrobenzene and 2-nitrotoluene

These were performed as described,³ and nitrobenzene was investigated in a similar manner.

Kinetic and product studies of the nitration of pyrazole and 1-nitropyrazole

In a dry glove box, dried F-720 or F-780 (0.15 g) and a magnetic follower in a reaction vessel were cooled to 0 °C. Dichloromethane (5 cm³) and N₂O₅ (0.35 g, 3.2 mmol) were added and stirred. After 10 minutes, a solution of pyrazole (0.0505 g, 0.742 mmol) or 1-nitropyrazole (0.0797 g, 0.705 mmol) and *p*-dinitrobenzene (internal NMR standard, 0.0138 g, 0.0821 mmol) in dichloromethane (1 cm³) was added.

Samples (0.3 cm³) were taken by syringe and forced through a syringe filter (to remove catalyst and stop further reaction) into specimen tubes at measured times. This method was used, rather than the aqueous quenching method,³ because of the high aqueous solubility of reactants and products. The samples were removed from the glove box, evaporated, dissolved in CDCl₃, and stored at -85 °C until analysed by ¹H NMR.

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References

- 1 K. Smith, T. Gibbins, R. W. Millar and R. P. Claridge, *J. Chem. Soc., Perkin Trans. 1*, 2000, 2753.
- 2 K. Smith, S. Almeer and S. J. Black, *Chem. Commun.*, 2000, 1571.
- 3 R. C. Claridge, N. L. Lancaster, R. W. Millar, R. B. Moodie and J. P. B. Sandall, *J. Chem. Soc., Perkin Trans. 2*, 1999, 1815.
- 4 J. G. Buchanan, M. Harrison, R. H. Wightman and M. R. Harnden, *J. Chem. Soc., Perkin Trans. 1*, 1989, 925.
- 5 H. Suzuki and N. Nonoyama, *J. Chem. Res. (S)*, 1996, 244.
- 6 *Solid Supports and Catalysts in Organic Synthesis*, K. Smith, Ed., Ellis Horwood Ltd., Chichester, 1992, p. 32.
- 7 M. Sierka, U. Eicher, J. Datka and J. Sauer, *J. Phys. Chem. B*, 1998, **102**, 6397.
- 8 N. C. Marziano, A. Tomasin, C. Tortato and J. M. Zaldivar, *J. Chem. Soc., Perkin Trans. 2*, 1998, 1973.
- 9 M. W. Austin, J. R. Blackborow, J. H. Ridd and B. V. Smith, *J. Chem. Soc.*, 1965, 1051.
- 10 R. Hüttel, F. Büchele and P. Jochum, *Chem. Ber.*, 1955, 1577.