

Lanthanide(iii) triflates as recyclable catalysts for atom economic aromatic nitration

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Lanthanide(m) triflates catalyse (1–10 mol%) the nitration of a range of simple aromatic compounds in good to excellent yield using stoichiometric quantities of 69% nitric acid; the only by-product is water and the catalyst can be readily recycled by simple evaporation.

Nitration of aromatic compounds is an immensely important industrial process.¹ The nitroaromatic compounds so produced are themselves widely utilised and act as chemical feedstocks for a great range of useful materials such as dyes, pharmaceuticals, perfumes and plastics. Unfortunately nitrations typically require the use of potent mixtures of concentrated or fuming nitric acid with sulfuric acid leading to excessive acid waste streams and added expense. Alternatively, nitric acid may be used in conjunction with strong Lewis acids such as boron trifluoride.² The Lewis acid is used at or above stoichiometric quantities and is destroyed in the aqueous quench liberating large amounts of strongly acidic by-products. With chemists under increasing pressure to perform atom economic processes³ with minimal or no environmentally unfriendly by-products, development of novel catalyst systems that facilitate aromatic nitrations in this manner should be of great importance.⁴

Lanthanides have found increasing use as mild and selective reagents in organic synthesis.⁵ In particular, lanthanide(iii) triflates^{6,7} have been used to good effect as Lewis acids in Diels–Alder,⁸ Michael,⁹ Friedel–Crafts¹⁰ and Mukaiyama¹¹ reactions. For the Mukaiyama reaction the optimum solvent system was found to be aqueous THF; the catalyst was recycled *via* aqueous work-up and used repeatedly with little detriment to rate or yield. The compatibility of lanthanide(iii) triflate salts with water and yet their apparent ability to function as strong Lewis acids is somewhat paradoxical. We sought to harness this water tolerant Lewis acidity and herein report the use of catalytic quantities of lanthanide(iii) triflates for the nitration of a range of simple aromatic compounds in good to excellent yield using a stoichiometric amount of 69% nitric acid where the only by-product is water. Furthermore the catalyst is readily recycled by a simple evaporative process.

Ytterbium(iii) triflate was selected as the most promising candidate for the proposed nitrations. Accordingly a range of simple aromatic compounds were treated with 1 equiv. of 69% nitric acid in 1,2-dichloroethane heated at reflux in the presence of 10 mol% ytterbium(iii) triflate. The results are shown in Table 1. No dinitrated products were observed in any case and in accord with this the system failed to nitrate nitrobenzene. In the control experiments with no catalyst, only slow reaction occurred and no more than 10% of nitrated products were observed. Ytterbium triflate was found to be effective even at catalyst loadings as low as 1 mol% and with *m*-xylene the reaction had proceeded to 80% conversion after 12 h.

The following procedure is representative. Nitric acid (69%; 192 μ l, 3.0 mmol) was added to a stirred suspension of ytterbium(iii) triflate (186 mg, 0.30 mmol) in 1,2-dichloroethane (5 ml). The suspension dissolved to give a two phase system in which the aqueous phase was the more dense. Toluene (240 μ l, 3.0 mmol) was added and the stirred mixture was heated at reflux for 12 h. During the reaction a white solid

precipitated and the organic phase became yellow, and after 12 h no phase boundary was apparent. The solution was allowed to cool and diluted with water. The yellow organic phase was dried (MgSO₄) and evaporated to give nitrotoluene (390 mg, 95%). The colourless aqueous phase was evaporated to give ytterbium(iii) triflate as a white free-flowing solid (183 mg, 98%).

A series of other metal triflate salts were screened for catalytic activity (Table 2). Scandium triflate was found to have comparable catalytic activity to that of the corresponding ytterbium salt, but praseodymium, europium and lanthanum triflates, although active, were found to be somewhat less effective.

The recovered catalyst was found to be active for further nitrations with no reduction in rate or yield and with no change in selectivity. The results from four successive nitrations with *m*-xylene are shown in Table 3. On one occasion the white precipitate obtained from the nitration mixture with lanthanum(iii) triflate consisted of crystals of the known lanthanum(iii) triflate nonahydrate.^{12†} These crystals were also found to have an identical diffuse reflectance IR spectrum to that of the amorphous recovered material and also that of the commercial

Table 1 Nitration of aromatics in the presence of ytterbium(iii) triflate^a

Arene	Conversion (%) ^{b,c}	Product distribution (%) ^c		
		<i>ortho</i>	<i>meta</i>	<i>para</i>
PhH	> 75 (75)	—	—	—
PhMe	> 95 (95)	52	7	41
PhPh	89	38	trace	62
PhBr	92	44	trace	56
PhNO ₂	0	—	—	—
<i>p</i> -xylene	> 95	—	—	—
<i>p</i> -dibromobenzene	8	—	—	—
<i>m</i> -xylene	> 95	4-NO ₂ : 85	—	2-NO ₂ : 15
naphthalene	> 95	1-NO ₂ : 91	—	2-NO ₂ : 9

^a All reactions carried out on a 3 mmol scale with 10 mol% ytterbium(iii) triflate and 1 equiv. of 69% nitric acid in refluxing 1,2-dichloroethane (5 ml) for 12 h. ^b Isolated yields in parenthesis. ^c GC and/or ¹H NMR analysis.

Table 2 Effect of lanthanide(iii) triflate on nitration of *m*-xylene^a

M(OTf) ₃ ^b	Conversion (%) ^c	Product distribution (%) ^c	
		4-NO ₂	2-NO ₂
La	22	86	14
Eu	36	86	14
Pr	65	88	12
Sc	85	85	15
Yb	88	85	15

^a All reactions performed with 10 mol% lanthanide(iii) triflate, 1 equiv. each of *m*-xylene and 69% nitric acid in refluxing dichloromethane (15 ml) for 18 h. ^b Commercially available hydrated forms. ^c GC analysis.

available lanthanide salt.[‡] As expected the crystals were found to catalyse the nitration reaction.

The nature of the *de facto* nitration agent is not known at present. The different rates with various lanthanide triflates indicate that the metal centre is involved. Nitric acid–triflic acid mixtures are known to effect nitration¹³ but free triflic acid seems unlikely in our system since ytterbium(iii) triflate yields a near-neutral solution when dissolved in water.[§] The relative ratios of the various nitroaromatic isomers produced are fully consistent with electrophilic attack by NO₂⁺ or more probably an NO₂⁺ carrier of the type **1**¹. However, bidentate lanthanide nitrates **2** are well characterised compounds,¹⁴ and nitration



may proceed *via* direct attack of such a (protonated) species. Bidentate metal nitrates have been implicated in nitrations with titanium tetranitrate¹⁵ and ceric ammonium nitrate¹⁶ where the arene is thought to attack the metal bound nitrate species directly.

In conclusion, we have demonstrated the catalytic use of lanthanide(iii) triflates for the atom economic nitration of simple aromatic substrates where the only by-product is water. The catalyst is readily recyclable and we believe this to be a major step forward in the area of clean technology for aromatic nitration.

The Imperial College group thank Air Products and Chemicals, Inc. for support of our research under the auspices of the joint Strategic Alliance, Glaxo Group Research Ltd. for the most generous endowment (to A. G. M. B.), the Wolfson Foundation for establishing the Wolfson Centre for Organic Chemistry in Medical Science at Imperial College, the EPSRC

Table 3 Recycled ytterbium(iii) triflate^a

Run	Conversion (%) ^b	Mass of catalyst/mg ^c
1	89	190 (> 100)
2	81	152 (82)
3	90	127 (68)
4	88	115 (62)

^a All runs performed with 3 mmol *m*-xylene, 10 mol% ytterbium triflate (run 1) and 1 equiv. of nitric acid in refluxing 1,2-dichloroethane (5 ml) for 5 h.

^b GC analysis. The isomeric ratio of 4- and 2-nitroxylene was unchanged throughout (85:15 respectively). ^c Mass of ytterbium(iii) triflate recovered from each run. The figures in parenthesis indicate the percentage recovery which were not optimised.

and Dr David Williams and Dr Andrew J. P. White for the single crystal X-ray structure determination of lanthanum(iii) triflate nonahydrate.

Footnotes

[†] A single crystal X-ray diffraction showed the material to be identical with the known lanthanum(iii) triflate nonahydrate where the nine water molecules occupy the first co-ordination sphere in a tricapped trigonal prism arrangement with triflate counterions

[‡] Aldrich chemical company

[§] The pH of a 0.08 M solution of ytterbium(iii) triflate in water was determined to be 6.40.⁷

References

- G. A. Olah, R. Malhotra and S. C. Narang, *Nitration: Methods and Mechanisms*, VCH, New York, 1989; C. K. Ingold, *Structure and Mechanism in Organic Chemistry*, Cornell University Press, Ithaca, New York, 2nd edn., 1969; G. A. Olah and S. J. Kuhn, in *Friedel-Crafts and Related Reactions*, ed. G. A. Olah, Wiley-Interscience, New York, 1964, vol. 2; K. Schofield, *Aromatic Nitrations*, Cambridge University Press, Cambridge, 1980.
- R. J. Thomas, W. F. Anzilotti and G. F. Hennion, *Ind. Eng. Chem.*, 1940, **32**, 408; G. F. Hennion, US Pat., 2314 212, 1943.
- B. M. Trost, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 259.
- For a recent nitration using clean methodology, see K. Smith, A. Musson and G. A. DeBoos, *Chem. Commun.*, 1996, 469. However this method suffers from the disadvantage of stoichiometric quantities of acidic by-products.
- T. Imamaoto, in *Lanthanides in Organic Synthesis*, Academic Press, London, 1994.
- R. W. Marshmann, *Aldrichim. Acta*, 1995, **28**, 77.
- S. Kobayashi, *Synlett*, 1994, 689.
- S. Kobayashi and H. Ishitani, *J. Am. Chem. Soc.*, 1994, **116**, 4083; I. E. Marko and G. R. Evans, *Tetrahedron Lett.*, 1994, **35**, 2771.
- S. Kobayashi, I. Hachiya, T. Takakori, M. Akida and H. Ishitani, *Tetrahedron Lett.*, 1992, **33**, 6815.
- A. Hachiya, M. Moriwaki and S. Kobayashi, *Bull. Chem. Soc. Jpn.*, 1995, **68**, 2053; A. Kawada, S. Mitamura and S. Kobayashi, *Chem. Commun.*, 1996, 183; A. Kawada, S. Mitamura and S. Kobayashi, *Synlett*, 1994, 545; A. Kawada, S. Mitamura and S. Kobayashi, *J. Chem. Soc., Chem. Commun.*, 1993, 1157.
- S. Kobayashi and I. Hachiya, *J. Org. Chem.*, 1994, **59**, 3590 and references cited therein.
- J. M. Harrowfield, D. L. Kepert, J. M. Patrick and A. H. White, *Aust. J. Chem.*, 1983, **36**, 483; A. Chatterjee, E. N. Maslen and K. J. Watson, *Acta Crystallogr., Sect. B.*, 1988, **44**, 381.
- C. L. Coon, W. G. Blucher and M. E. Hill, *J. Org. Chem.*, 1973, **38**, 4243.
- F. A. Cotton and G. Wilkinson, *Advanced Inorganic Chemistry*, Wiley, New York, 4th edn., 1980, pp. 173, 981–1004.
- D. W. Amos, D. A. Baines and G. W. Flewett, *Tetrahedron Lett.*, 1973, 3191.
- S. Dincturk and J. H. Ridd, *J. Chem. Soc., Perkin Trans. 2*, 1982, 961.

Received, 23rd January 1997; Com. 7/00546F