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$Sc(OTf)_3$-catalyzed carbomethoxylation of aliphatic amines with dimethyl carbonate (DMC): DMC activation by η^1-O(C=O) coordination to Sc(III) and its relevance to catalysis

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Abstract

The role of metal center in the $Sc(OTf)_3$-catalyzed carbomethoxylation of aliphatic amines with DMC has been investigated. We have shown that the catalytic formation of carbamate ester is promoted by coordination of DMC to scandium(III) ion through the carbonyl oxygen atom. The ability of DMC to coordinate to Sc(III) has been proved by IR and NMR spectroscopy and fully demonstrated also by the isolation, for the first time, of a DMC–metal complex characterized as $(\eta^1$-O(C=O)–DMC)$Sc(OTf)_3$. A relationship has been shown between the coordination mode of DMC to Sc(III) and the reactivity of coordinated organic carbonate: coordination of DMC to Sc(III) activates both carbonyl group and O–CH_3 moieties of the carbonic acid diester and enhances not only the carbomethoxylating but also the methylating activity of the ambident electrophile (DMC), as documented by the different selectivity exhibited by the catalyst in the aminolysis reaction of DMC with benzylamine and aniline, respectively.

Keywords: Amines; Carbamates; Dimethyl carbonate; Homogeneous catalysis; Transition metal catalysts; Scandium

1. Introduction

The reaction of amines with organic carbonates

$$RNH_2 + R'OC(O)OR' \xrightarrow{(cat.)} RNHC(O)OR' + R'OH,$$
$$R' = \text{alkyl, aryl,} \qquad (1)$$

is an environmentally benign synthetic route to carbamate esters [1–10], which is potentially alternative to the current methods of synthesis based on toxic and harmful phosgene [11]. The interest for this innovative approach to the synthesis of carbamates is very widespread and, in this context, many efforts are currently being turned to the utilization of dimethyl carbonate (DMC) [1,12], which is receiving growing attention as safe, non-toxic, eco-friendly carbomethoxylating [13–28] or, more generally, carbonylating [29] agent in place of phosgene.

The carboalkoxylation reaction [Eq. (1); R′ = Me, Et, alkyl] requires a suitable catalyst able to promote the relevant process at acceptable conversion rate and with satisfactory carbamate selectivity. In fact, the formation of by-products, such as *N*-alkyl-amines, *N*-alkyl-carbamates, ureas, is often a serious drawback which lowers the selectivity of the carbamation reaction. The search for selective catalysts is a major task in this field and many catalytic systems have been employed so far, such as enzymes [13,14], ionic liquids [15], organic bases [6,16,28], Brønsted acids [3], metal derivatives (oxides, salts or complexes) [2,17–24] and, even, carbon dioxide [25–27].

However, despite the number of catalytic systems explored, only in a few cases the role of catalyst has been probed. The catalytic activity of alkali alkoxides has been related with their ability of exalting the nucleophilic character of amine [28]. A few organocatalysts catalyze the carbamation process by activating the organic carbonate through the formation of a suitable reactive intermediate [3–6,25,26]. In previous studies, for instance, we have shown that organophosphorous Brøn-

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sted acids $X_2P(O)OH$ (X = Ph, PhO, BuO) or, also, CO_2 itself promote, respectively, the carbomethoxylation of primary amines with DMC through the formation of very reactive organophosphoric–carbonic ($X_2P(O)OC(O)OMe$) [3] or carbamic–carbonic (RNHC(O)OC(O)OMe) [25,26] mixed anhydrides. As for metal-salt or metal-complex catalysts, activation of substrate (organic carbonate) by coordination to the metal center has been often invoked [2,17,22], but in most cases without the support of any experimental evidence.

In a few recent studies [21,24] we have shown that, under very mild conditions, $Sc(OTf)_3$ is an effective and selective catalyst for carbamation of aliphatic mono- and di-amines with DMC. The catalytic process can be carried at ambient temperature in DMC, used both as reagent and solvent, and proceeds with high yield (isolated carbamate yields >80%) and selectivity (>99%). In this work we focus on the metal salt ($Sc(OTf)_3$) used as carbomethoxylation catalyst with the view of elucidating the role of metal center in the catalytic process [Eq. (1); R′ = Me; cat. = $Sc(OTf)_3$]. Herein, we demonstrate the central role of DMC coordination to Sc(III) in the catalytic process. Through this step the substrate (DMC) is activated at the carbonyl group toward the nucleophilic attack by aliphatic amine. However, DMC coordination to scandium also activates the O–Me moieties of the organic carbonate and enhances the methylating reactivity of the substrate, as documented by the activity of the salt in the catalytic reaction of DMC with an aromatic amine such as aniline.

2. Experimental

2.1. General

Unless otherwise stated, all reactions and manipulations were conducted under an inert gas atmosphere, by using vacuum line techniques. All solvents were dried according to literature methods [30] and stored under N_2. DMC (Fluka) was dried over 5A molecular sieves for 24 h, filtered, distilled, and stored under N_2. Amines were dried over KOH, distilled, and stored under N_2. $Sc(OTf)_3$ (99.995%, Aldrich) was used as received and manipulated under a dinitrogen atmosphere.

GC analyses were performed with a HP 5890 Series II gas-chromatograph (capillary column: Heliflex AT-5, 30 m × 0.25 mm, 0.25 μm film thickness). GC-MS analyses were carried out with a Shimadzu GC-17A linked to a Shimadzu GCMS-QP5050 selective mass detector (capillary column: Supelco MDN-5S, 30 m × 0.25 mm, 0.25 μm film thickness).

IR spectra were taken on a Perkin Elmer FTIR 1710 spectrophotometer or with a Shimadzu FTIR Prestige 21 instrument, at room temperature, over a range 4000–400 cm^{-1}. The spectra of solutions were run in a 0.1 or 0.012 mm KBr or CaF_2 cell. For further experimental details, see also Section 3.2.1 and the captions of Figs. 3–5.

NMR spectra were run with a Bruker AM 500 spectrometer or with a Varian Mercury 300 or a Varian Inova 400 instrument. Chemical shifts are in δ (ppm) vs TMS (^1H, ^{13}C) or $CFCl_3$ (^{19}F).

2.2. Catalytic carbomethoxylation of RNH_2 (R = i-butyl, n-butyl, benzyl, phenyl) in the presence of triflate salts: general procedure

The reaction was carried out in 10 mL Schlenk tube. To a DMC solution containing a catalytic amount of triflate salt, $M(OTf)_3$ (M = Sc, La) or $(PhCH_2NH_3)OTf$, the amine and *n*-undecane (internal standard) were added. The reaction mixture was allowed to react at the working temperature (293 or 363 K) and, at measured intervals of time, analyzed by GC (see also Tables 1 and 3 and the legends of Figs. 1 and 2).

2.3. Influence of O-donors on the carbomethoxylation of benzylamine catalyzed by $Sc(OTf)_3$: experimental procedure

A solution of $Sc(OTf)_3$ (0.13280 g, 0.270 mmol) in DMC (4 mL) was prepared. To an aliquot (1.1 mL) of the above solution the O-donor, if used [THF (0.076 mL, 0.936 mmol) or methanol (0.038 mL, 0.939 mmol)], benzylamine (0.100 mL, 0.916 mmol) and *n*-undecane (0.030 mL, 0.142 mmol; internal standard) were added in sequence. The reaction mixture was allowed to react at ambient temperature (293 K) and, at measured intervals of time, analyzed by GC (see also Fig. 6).

2.4. Catalytic carbomethoxylation of 1,6-diaminohexane promoted by $Sc(OTf)_3$: experimental procedure

The reaction was carried out in a 100 mL Schlenk tube which was charged with the catalyst ($Sc(OTf)_3$: 2.6 mol% vs diamine), DMC, THF, if used, and 1,6-diaminohexane. The reaction mixture was allowed to react at ambient temperature (293 K) under vigorous stirring. The conversion of the diamine into mono- and di-carbamate ($H_2N(CH_2)_6NHC(O)OMe$ and $MeO(O)CNH(CH_2)_6NHC(O)OMe$) was monitored by GC and/or GC-MS (see also Table 2).

2.5. Measurement of ^{13}C NMR coordination shifts of DMC in the presence of $Sc(OTf)_3$

The ^{13}C NMR coordination shifts for DMC coordinated to scandium ion in CH_2Cl_2 and CH_3CN were measured, respectively, at 125 and 75 MHz. External referencing was used for scale calibration. Chemical shifts were referenced to the ^{13}C signals of the external reference (C_6D_6 or acetone-d_6, contained in a coaxial capillary tube) and reported in δ (ppm) vs TMS.

2.5.1. ^{13}C NMR coordination shifts of DMC in the presence of $Sc(OTf)_3$, in CH_2Cl_2

The ^{13}C spectrum (125 MHz, 293 K; ext. ref.: C_6D_6) of a solution of DMC (0.120 mL, 1.424 mmol) and $Sc(OTf)_3$ (0.12260 g, 0.249 mmol) in CH_2Cl_2 (5 mL) was taken (δ = 157.41 (*C*=O, DMC), 56.32 (O*C*H$_3$, DMC), 119.34 (q, $^1J_{CF}$ = 316 Hz, O_3SCF_3), 127.97 (t, $^1J_{CD}$ = 23.5 Hz, C_6D_6), 54.02 (CH_2Cl_2)) and compared with the spectrum (125 MHz, 293 K; ext. ref.: C_6D_6) of a CH_2Cl_2 (5 mL) solution of DMC (0.120 mL, 1.424 mmol), not containing $Sc(OTf)_3$ (δ = 156.52 (*C*=O, DMC), 54.87 (O*C*H$_3$, DMC), 127.97 (t, $^1J_{CD}$ =

23.5 Hz, C_6D_6), 54.05 (CH_2Cl_2)). The measured coordination shifts ($\Delta\delta$) of carbonyl and methoxyl carbon atoms of DMC were equal to +0.89 and +1.45 ppm, respectively.

2.5.2. ^{13}C NMR coordination shifts of DMC in the presence of $Sc(OTf)_3$, in CH_3CN

The ^{13}C spectrum (75 MHz, 293 K; ext. ref.: acetone-d_6) of a solution of DMC (0.110 mL, 1.307 mmol) and $Sc(OTf)_3$ (0.05395 g, 0.110 mmol) in CH_3CN (1 mL) was run (δ = 157.06 (C=O, DMC), 55.32 (OCH_3, DMC), 122.02 (coordinated CH_3CN), 117.92 (free CH_3CN), 1.31 (CH_3CN), 206.05 (CD_3COCD_3), 29.79 (sept, $^1J_{CD}$ = 19 Hz, CD_3COCD_3); after 512 transients, the quartet of O_3SCF_3 was not yet evident in the spectrum) and compared with the spectrum (75 MHz, 293 K; ext. ref.: acetone-d_6) of a CH_3CN (1 mL) solution of DMC (0.110 mL, 1.307 mmol), not containing $Sc(OTf)_3$ (δ = 156.86 (C=O, DMC), 55.00 (OCH_3, DMC), 117.95 (CH_3CN), 1.38 (CH_3CN), 206.05 (CD_3COCD_3), 29.79 (sept, $^1J_{CD}$ = 19 Hz, CD_3COCD_3)). The measured coordination shifts ($\Delta\delta$) of carbonyl and methoxyl carbon atoms of DMC were equal to +0.20 and +0.32 ppm, respectively.

2.6. Stoichiometry and characterization of the $Sc(OTf)_3$–DMC adduct

A solution of $Sc(OTf)_3$ (0.250 g, 0.508 mmol) in DMC (5 mL) was stirred for half an hour and then evaporated in vacuo for 24 h to afford a very viscous residue, whose IR spectrum (neat) showed bands at $\tilde{\nu}$ = 2978 (mw), 2936 (w), 2891 (w), 1638 (vs, ν(C=O)), 1508 (s, $\delta(CH_3)$), 1458 (m, $\delta(CH_3)$), 1431 (ms, $\delta(CH_3)$), 1344 (vs, broad), 1238 (s), 1202 (vs), 1113 (m), 1018 (s), 935 (w, ν_{asymm}(O–CH_3)), 881 (ms, ν_{symm}(O–CH_3)), 793 (ms, $\delta(OCO_2)$), 768 (m), 637 (s), 586 (ms), 571 (m), 509 cm^{-1} (ms). A weak band was also present at 1760 cm^{-1} and assigned to minor amounts of free DMC. Further purification of the product was prevented by its high lability in solution (see also Section 3.4).

The DMC/$Sc(OTf)_3$ molar ratio in the isolated product, as determined by measuring the ratio of integrals for the resonances due to the –CF_3 and –OCH_3 groups in the inverse gated decoupled ^{13}C NMR spectrum (100 MHz) of the product dissolved in DMSO-d_6 (used conditions: spectral width = 13074 Hz, acquisition time = 1.2 s, pw = 90° (10.2 μs), pulse delay = 60 s, number of transients = 3256), was found to be equal to 1.0 mol/mol. This value agreed well with the value of 1.1 mol/mol calculated from the ^1H (400 MHz; spectral width = 6000 Hz, acquisition time = 6 s, pw = 90° (10 μs), pulse delay = 30 s, number of transients = 108) and ^{19}F (376 MHz; spectral width = 52770 Hz, acquisition time = 2.57 s, pw = 90° (12.7 μs), pulse delay = 15 s, number of transients = 128) NMR integral spectra of the product in a DMSO-d_6 solution containing 1-bromo-2,4,5-trifluorobenzene as internal standard.

NMR of (DMC)$Sc(OTf)_3$. ^1H NMR (400 MHz, 293 K, DMSO-d_6): δ = 3.64 (s, OCH_3). ^{13}C NMR (100 MHz, 293 K, DMSO-d_6): δ = 54.96 (OCH_3), 121.00 (q, ^1J(C,F) = 322 Hz, CF_3), 156.09 (C=O). ^{19}F NMR (376 MHz, 293 K, DMSO-d_6): $\delta = -77.76$ (CF_3).

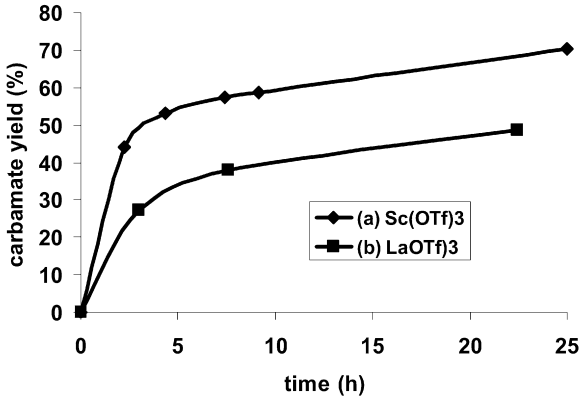


Fig. 1. Carbomethoxylation of i-butylamine with DMC in the presence of $M(OTf)_3$ (M = Sc, La) at 293 K. DMC: 11.9 mmol; i-$BuNH_2$: 0.90 mmol. (a) $Sc(OTf)_3$: 7.4 mol% vs the amine; (b) $La(OTf)_3$: 7.8 mol% vs the amine.

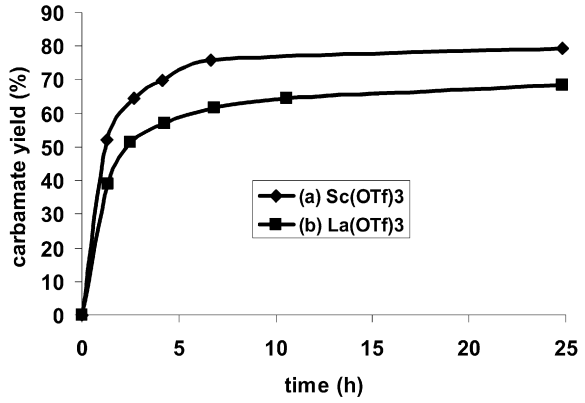


Fig. 2. Carbomethoxylation of n-butylamine with DMC in the presence of $M(OTf)_3$ (M = Sc, La) at 293 K. DMC: 11.9 mmol; n-$BuNH_2$: 0.91 mmol. (a) $Sc(OTf)_3$: 7.5 mol% vs the amine; (b) $La(OTf)_3$: 7.7 mol% vs the amine.

3. Results and discussion

3.1. Catalytic role of the metal center (Sc(III))

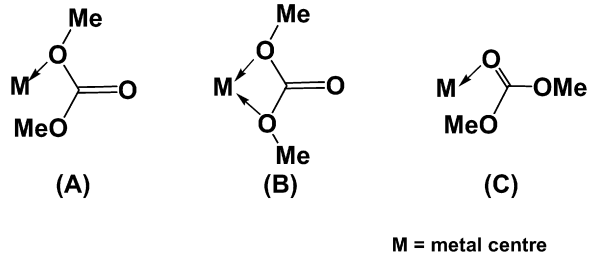
The activity of $Sc(OTf)_3$ as carbomethoxylation catalyst of aliphatic mono- and di-amines [Eq. (1); R′ = Me, cat. = $Sc(OTf)_3$)] under a variety of conditions (T: 293–363 K; DMC/amine molar ratio: 13–0.3 mol/mol; catalyst loading: 0.6–10 mol% vs amine) and the synthetic applications of the catalytic process have been fully documented elsewhere [21,24]. The metal center (Sc(III)) takes part actively in the catalytic process. As a matter of fact, under comparable reaction conditions, other OTf salts, such as $La(OTf)_3$ or ($RR'NH_2$)OTf (R = alkyl; R′ = H, alkyl), are less effective catalysts. Figs. 1 and 2, for instance, compare the behavior of $Sc(OTf)_3$ and $La(OTf)_3$ in the carbomethoxylation of i- and n-butyl-amine. Moreover, Table 1 shows clearly that a non-metal triflate salt, such as ($PhCH_2NH_3$)OTf, has a negligible catalytic activity.

In principle, the activity exhibited by $Sc(OTf)_3$ may be related with the oxophilicity of the metal center [31,32], which

Table 1
Carbomethoxylation of $PhCH_2NH_2$ with DMC in the presence of triflate salts at 293 K[a,b]

Entry	Triflate salt	Triflate salt/amine (mol%)	Time (h)	$PhCH_2NHC(O)OMe$ yield[c] (%)
1	$Sc(OTf)_3$	7.9	21	75
2	$(PhCH_2NH_3)OTf$	28	19	10

[a] $PhCH_2NH_2$: 0.92 mmol; DMC: 11.9 mmol. In all the runs.
[b] In the absence of any catalyst carbamate yield was equal to 2% after 17 h.
[c] GC yield vs the amine.



Scheme 1. Coordination modes of DMC.

may coordinate and activate the O-donor substrate (DMC). In order to support this hypothesis experimentally, we have investigated the coordinating properties of DMC toward $Sc(OTf)_3$, both in coordinating (CH_3CN, THF, MeOH, H_2O) and non-coordinating (CH_2Cl_2) solvents, using IR and ^{13}C NMR spectroscopies as main diagnostic tools.

3.2. IR studies

Scheme 1 illustrates the possible basic modes through which DMC can bind to a d^0 metal center, such as Sc(III). Coordination modes (A) and (B) involve the ester O-atoms of DMC molecule (one or both, respectively). Mode (C) implicates η^1-O(C=O) coordination of DMC molecule through the carbonyl oxygen.

Coordination of DMC to a metal center is expected to induce marked structural perturbations, such as bond-length changes, in the coordinated molecule and, consequently, cause the shift of appropriate bond vibration stretching frequencies with respect to the free molecule [33]. According to a description of inductive effects on chemical bonds [34–37], both the coordination modes (A) and (B) are expected to strengthen the C=O bond and, consequently, should cause ν(C=O) to increase with respect to the value observed in the free molecule [33]. Different effects can be anticipated for binding mode (C). This interaction should lengthen (weaken) the C=O and O–Me bonds and shorten (strengthen) the C–O ones [34–37] and, therefore, induce (i) a negative shift (to lower wavenumbers) of ν(C=O), while (ii) the stretching frequencies associated with O–C–O and O–CH_3 bonds are expected to shift toward opposite directions (to blue and red, respectively). The latter features find an experimental support in the spectroscopic (IR) data collected for η^1-O(C=O) adducts of several metal salts with various carbonyl compounds (carboxylic acid esters, amides, lactames, etc.) [34–40].

IR studies on the coordination of DMC or other organic carbonates to metal centers are rare in the literature. It has been reported that the presence of MeOH can promote the coordination of DMC to $Zn(O_2CCH_3)_2{\cdot}2H_2O$ [22]. The appearance of a band at 1722 cm^{-1} in the IR spectrum of a $CHCl_3$ solution containing the organic carbonate, the salt and the alcohol was adduced as evidence of formation of a η^1-O(C=O) DMC–Zn(II) adduct. Another recent study [41] has considered the binding properties of DMC toward Na^+ cations to explain the IR spectrum of DMC in the restricted spaces of supercages of NaY zeolites. Theoretical calculations support the formation of both (B)- and (C)-like adducts (Scheme 1, M = Na^+). The experimental spectra do not provide any data for the shifts of $\nu_{asymm/symm}(OCH_3)$ modes, whose absorptions fall within the zeolite framework region, but they indicate that ν(C=O) and ν_{asymm}(OCO) modes are, respectively, blue- and red-shifted with respect to free DMC in the (B)-like adduct (M = Na^+), while undergo an opposite shift in the (C)-like DMC–Na^+ species [ν(C=O): to red; ν_{asymm}(OCO): to blue].

3.2.1. Coordination of DMC to $Sc(OTf)_3$: IR evidences

The IR spectrum of anhydrous $Sc(OTf)_3$ in the solid state was studied by Pascal and co-workers [42]. The presence of bands in the range 1300–1350 cm^{-1} indicates that OTf is coordinated to the metal center [42–45]. The anion acts as a bridging bidentate ligand, providing, thus, an octahedral environment around Sc^{3+} ion [42].

The salt is poorly soluble in a non-coordinating solvent such as CH_2Cl_2 and, in fact, the IR spectrum ((a) in Fig. 3) of a solution obtained by equilibrating CH_2Cl_2 with $Sc(OTf)_3$, under an inert atmosphere, was practically superimposable to that of pure CH_2Cl_2. Addition of a DMC excess (5.2 mol per mol of Sc) to a suspension of $Sc(OTf)_3$ in CH_2Cl_2 caused the almost complete solubilization of the salt. Consequently, in addition to the absorptions due to free DMC (at 2959, 1751, 1605, 1590, 1455, 1430, 1279, 970, 916 and 794 cm^{-1}; see also spectrum (b) in Fig. 3), the IR spectrum of the resulting solution ((c) in Fig. 3) showed the appearance of intense OTf bands in the region 1350–1000 cm^{-1}, where $\nu_{asymm/symm}(SO_3)$ and $\nu_{asymm/symm}(CF_3)$ vibration modes strongly absorbs [42–45]. New absorptions were also clearly evident at 1646 and 1504 cm^{-1}.

These results show unambiguously that, in a non-coordinating solvent, such as CH_2Cl_2, $Sc(OTf)_3$ can interact with the organic carbonate to give a soluble adduct in equilibrium with free DMC:

$$Sc(OTf)_{3\,(s)} + x\,DMC_{(sol)} \overset{CH_2Cl_2}{\rightleftarrows} (DMC)_x Sc(OTf)_{3\,(sol)}. \qquad (2)$$

The absorption around 1350 cm^{-1} ((c) in Fig. 3) reveals that, in the complex, scandium ion still accommodates OTf ligands in its coordination sphere (see also, below, the behavior in CH_3CN and THF). DMC coordination to Sc is strongly supported by the band at 1646 cm^{-1}, which can be assigned to the stretching of coordinated DMC carbonyl group, ν(C=O), in the adduct. The shift to red ($\Delta\nu$(C=O) < 0) allows us to exclude coordination modes like (A) or (B) (Scheme 1), for which a positive shift

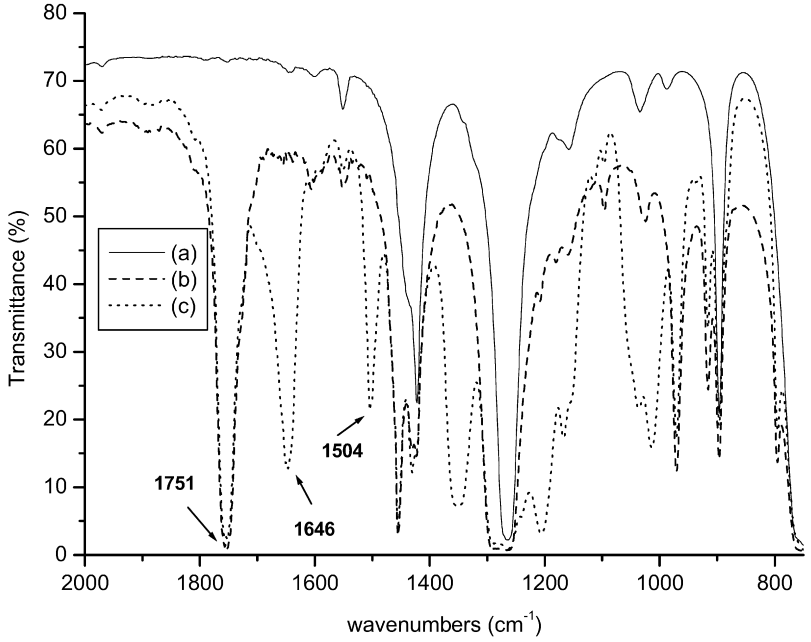


Fig. 3. IR spectra (2000–750 cm^{-1}) of (a) CH_2Cl_2 (2.5 mL) equilibrated with solid $Sc(OTf)_3$ (63.50 mg, 0.129 mmol); (b) DMC (0.060 mL, 0.712 mmol) in CH_2Cl_2 (2.0 mL); (c) a solution obtained by adding DMC (0.060 mL, 0.712 mmol) to a suspension of $Sc(OTf)_3$ (66.90 mg, 0.136 mmol) in CH_2Cl_2 (2.0 mL).

($\Delta\nu$(C=O) > 0) should be expected, and points to coordination mode (C) as the most likely one.

Differently from CH_2Cl_2, CH_3CN dissolves $Sc(OTf)_3$ fairly well. The IR spectrum of a CH_3CN (1.0 mL) solution of $Sc(OTf)_3$ (45.85 mg, 0.0932 mmol) showed a band at 1341 cm^{-1}, indicative of coordinated triflate, and other OTf absorptions at 1271, 1239, 1207, 1161, 1034, 640, 595, 572 and 512 cm^{-1}. A medium-sharp ν(C≡N) band at 2316 cm^{-1}, absent in the spectrum of pure CH_3CN, is diagnostic of η^1-N(C≡N) coordination of acetonitrile to Sc(III) [46,47]:

$$Sc(OTf)_3 + xCH_3CN \rightleftarrows (CH_3CN)_xSc(OTf)_3. \quad (3)$$

This band was still clearly observable also when DMC (0.045 mL, 0.534 mmol) was added to the CH_3CN solution (0.7 mL) of the scandium salt (DMC/Sc: 8 mol/mol). After addition of DMC, the IR spectrum of the resulting solution showed, besides the bands due to free DMC, a new medium absorption at 1659 cm^{-1} assigned to DMC η^1-O(C=O) coordinated to Sc(III).

We have investigated the behavior of the DMC–$Sc(OTf)_3$ system also in O-donor solvents such as THF [48], MeOH [49,50] and H_2O [51], in which $Sc(OTf)_3$ is easily soluble.

Addition of DMC (0.050 mL, 0.593 mmol) to a solution of $Sc(OTf)_3$ (0.056 g, 0.095 mmol) in anhydrous MeOH (1.0 mL) did not cause, in the spectrum of the resulting solution, the appearance of any new IR band which can be assigned to bound DMC. Likewise, no bands due to coordinated DMC were found in a D_2O (1.5 mL) solution of $Sc(OTf)_3$ (139.3 mg, 0.283 mmol) containing the organic carbonate (0.2 mL, 2.4 mmol). This fact and the absence of any band in the range 1350–1340 cm^{-1} due to OTf ligand are consistent with the presence in solution of only fully ionic aqua-scandium triflate species, $[Sc(D_2O)_x](OTf)_3$ [51].

After adding DMC to $Sc(OTf)_3$ (0.122 mmol; DMC/Sc = 1:1 mol/mol) in THF (1.0 mL), no absorptions due to coordinated DMC were located in the IR spectrum of the solution in addition to the bands of solvent, OTf (1353, 1236, 1200–1000, 766, 638, 591 and 565 cm^{-1}) and those due to free DMC. However, further addition of DMC to the solution (DMC/Sc: 8 mol/mol) caused the appearance of a weak band at 1653 cm^{-1}, which can be attributed to coordinated DMC. The low intensity of this absorption at 1653 cm^{-1} and the behavior observed in MeOH and H_2O indicate that the coordinating ability of DMC toward $Sc(OTf)_3$ decreases somewhat in O-donor solvents, like those here investigated. This conclusion was also supported by the results of a few competitive experiments. In fact, after addition of THF (0.250 mL, 3.10 mmol) to a CH_2Cl_2 solution (3.5 mL) of DMC (0.28 M; THF/DMC: 3.2 mol/mol) containing $Sc(OTf)_3$ (0.05 M), the band at 1646 cm^{-1}, assigned to coordinated DMC (see also spectrum (c) in Fig. 3), was replaced by a much weaker absorption at 1655 cm^{-1}. When H_2O (0.003 mL, 0.167 mmol) was added to 0.5 mL of a CH_2Cl_2 solution of DMC (0.28 M) and $Sc(OTf)_3$ (0.05 M; H_2O/DMC/Sc = 6.7:5.6:1 mol/mol) a white precipitate separated fast. The IR spectrum of the solution showed the drastic reduction or complete disappearance of the absorptions due to coordinated DMC (1646 and 1504 cm^{-1}) and triflate. The latter findings are consistent with the formation of ionic species $[Sc(H_2O)_x](OTf)_3$, poorly soluble in the solvent used (CH_2Cl_2).

Therefore, DMC can η^1-O(C=O) bind to $Sc(OTf)_3$. However, in O-donor solvents, which may effectively compete with the organic carbonate for the coordination sites of the strongly oxophilic metal center, the coordinating ability of DMC toward $Sc(OTf)_3$ is markedly repressed and in MeOH or H_2O no evidence of DMC coordination to $Sc(OTf)_3$ was found

by IR spectroscopy. The measured shift, $\Delta\nu$(C=O), ranges around -100 cm^{-1} and slightly changes with the solvent used. $\Delta\nu$(C=O) is larger than that observed for coordination compounds of ScX_3 (X = NO_3, Cl, Br, SCN, ClO_4) salts with lactames ($\Delta\nu$(C=O) = -39 to -47 cm^{-1}) [40] and amides ($\Delta\nu$(C=O) = -23 to -25 cm^{-1}) [39] or for adducts of $ScCl_3$ with ketones ($\Delta\nu$(C=O) = -43 to -80 cm^{-1}) [38], and is comparable with that measured for complexes of $ScCl_3$ with esters of carboxylic acids ($\Delta\nu$(C=O) = -90 to -140 cm^{-1}) [38]. The shift is also markedly larger than that ascribed to the formation of (C)-like adducts between DMC and Zn^{2+} (from $Zn(O_2CCH_3)_2{\cdot}2H_2O$; $\tilde{\nu}$(C=O) = 1722 cm^{-1}) [22] or Na^+ cations of NaY supercages ($\tilde{\nu}$(C=O) = 1747 cm^{-1}) [41]. This trend can be related to the diverse nature of the metal centers (M = Na^+, Zn^{2+}, Sc^{3+}) and their different acceptor-strengths and suggests a stronger donor–acceptor interaction for the couple Sc(III)–DMC.

3.3. Coordination of DMC to Sc(OTf)$_3$: ^{13}C NMR studies

Coordination of DMC to scandium ion modifies also the electron density at the carbon nuclei of the organic carbonate and is expected to shift the ^{13}C resonances of coordinated DMC with respect to those of the free molecule. Therefore, the interaction of the organic carbonate with the salt ($Sc(OTf)_3$) has been investigated also by ^{13}C NMR spectroscopy. ^{13}C NMR studies on coordination of DMC or other organic carbonates to metal centers are relatively few and deal with adducts of such substrates with lithium ions [52,53].

We have found that the ^{13}C NMR (125 MHz, 293 K; ext. ref.: C_6D_6) spectrum of a CH_2Cl_2 solution of $Sc(OTf)_3$ and DMC (DMC/Sc: 5.7 mol/mol) showed, in addition to the CF_3 resonance of OTf, only two signals for DMC, at 157.41 (C=O) and 56.32 (OCH$_3$) ppm. Both DMC resonances were down field shifted ($\Delta\delta$ = +0.89 and +1.45 ppm, respectively) with respect to those (156.52 (C=O) and 54.87 ppm (OCH$_3$)) observed in the ^{13}C NMR (125 MHz, 293 K; ext. ref.: C_6D_6) spectrum of a CH_2Cl_2 solution of DMC of equal concentration. An analogous down field shift was observed for both DMC resonances (C=O and OCH$_3$) also in the ^{13}C NMR (75 MHz, 293 K; ext. ref.: acetone-d_6) spectrum of a CH_3CN solution of $Sc(OTf)_3$ and DMC (DMC/Sc: 11.9 mol/mol). However, with respect to a CH_3CN solution of DMC of equal concentration, the magnitude of shifts was, in this case, more modest ($\Delta\delta$ = +0.20 ppm (C=O) and +0.32 ppm (OCH$_3$)).

The shifts observed for both the ^{13}C signals of DMC in the presence of $Sc(OTf)_3$ further confirm the ability of the organic carbonate to interact with the salt in the solvents used. The presence of a unique set of DMC resonances for both coordinated and free DMC indicates that, under the working conditions (293 K), free and coordinated DMC molecules exchange fast with respect to the chemical shift time scale. The above findings agree well with those reported in the literature for adducts of DMC or other organic carbonates with lithium ions [52,53]. The interaction of DMC with lithium ion deshields both carbonyl and methoxyl carbon nuclei of DMC [52], mainly because of decrease of electron density around these nuclei upon η^1-O(C=O) coordination of the organic carbonate to Li^+ [52,53]. However, the methoxyl shift (comparable with that of carbonyl) has not been related merely to the change of net charge on the methoxyl C-atoms of DMC η^1-O(C=O)-coordinated to Li^+, but has been ascribed also to conformational changes during coordination or to some direct contribution of coordination modes involving the ester O-atoms [52,53]. In our case, despite the down field shift observed for OCH$_3$ carbons is even larger than that of C=O group, the presence in solution of adducts like (A) or (B) (Scheme 1, M = Sc^{3+}) can be considered very unlikely, as under experimental conditions analogous or comparable with those used in the NMR experiments, we have never obtained any IR evidence supporting DMC coordination to scandium through the ester oxygens ($\Delta\nu$(C=O) > 0).

3.4. Characterization of the Sc(III)–DMC adduct

The Sc(III)–DMC adduct has been isolated from a DMC solution of $Sc(OTf)_3$, as described in Section 2, and its stoichiometry (1:1) determined by means of quantitative NMR (^{13}C, ^{1}H, ^{19}F) analysis.

Fig. 4 compares the IR spectra of the adduct and liquid DMC (for a detailed analysis of the IR spectrum of liquid DMC see [33]). The IR spectrum of (DMC)$Sc(OTf)_3$ shows, in addition to the OTf absorptions (1344, 1238–1202, 1018, 637, 586 and 509 cm^{-1}) [42–45], other bands at 1638, 1508, 1458, 1431, 935, 881, 793 cm^{-1}. Triflate anion (or ligand) does not absorb in these regions [42–45] and, therefore, these absorptions can be attributed to coordinated DMC without any doubt. The positions of the signals at 1638 (ν(C=O)) and 1508 ($\delta(CH_3)$) cm^{-1} agree well with those of the bands at 1646 and 1504 cm^{-1} observed in CH_2Cl_2 solution (spectrum (c) in Fig. 3). The inspection of Fig. 4 (see also [33]) allows to locate the signals associated with the ν_{asymm}(O–CH_3) and ν_{symm}(O–CH_3) vibrational modes of the adduct, which are found, respectively, at 935 and 881 cm^{-1}. As expected (see Section 3.2), η^1-O(C=O) coordination of the organic carbonate to the metal center shifts to red not only ν(C=O) (1759 cm^{-1} for liquid DMC), but also both asymmetric and symmetric CH_3–O stretching frequencies (respectively at 970 and 914 cm^{-1} for liquid DMC). Unfortunately, we cannot locate the absorptions due to the asymmetric and symmetric ν(OCO) vibrations. These bands, which are observed, respectively, at 1277 (vs) and 1117 (w) cm^{-1} in the spectrum of liquid DMC, are expected to be blue-shifted in the adduct and, most likely, are masked by the strong absorptions due to OTf groups at 1342 and 1238–1202 cm^{-1}.

The complex is extremely hygroscopic and, as established by IR spectroscopy, rapidly decomposes upon exposure to air, even for short times ($\approx$ 1 min). In solution, in the absence of any excess of DMC, the stability of the adduct is very modest as the complex easily looses coordinated DMC. For instance, upon treating the complex with anhydrous CH_2Cl_2, a white solid separated from the solution, and the IR spectrum of the solution (similar to spectrum (c) reported in Fig. 3) showed, in addition to the bands at 1646 and 1505 cm^{-1}, a strong absorption at 1752 cm^{-1} due to free DMC. This behavior can

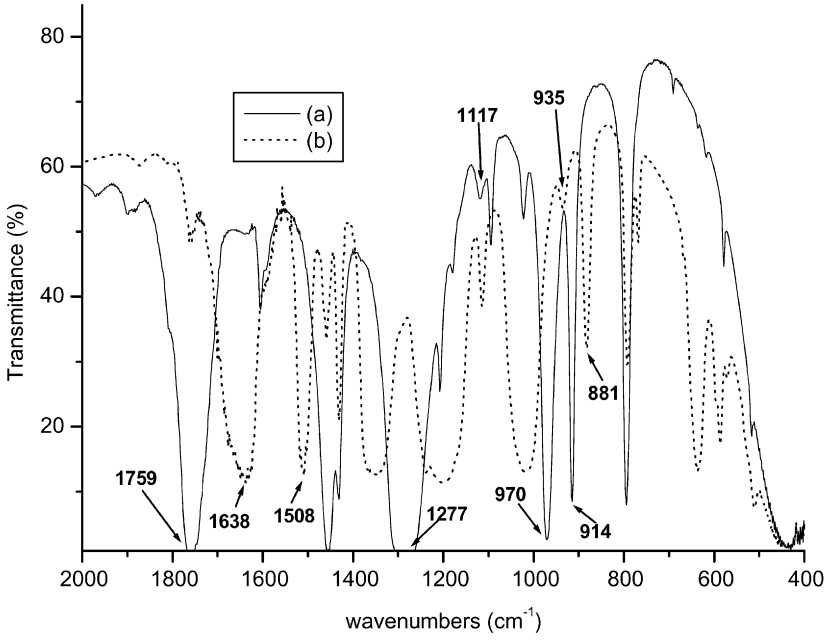


Fig. 4. IR spectra (2000–400 cm^{-1}): (a) DMC (neat); (b) (DMC)$Sc(OTf)_3$ (neat).

be easily explained in terms of reverse of equilibrium (2). An analogous behavior was observed in CH_3CN or water. In these solvents the complex was completely soluble. However, the resulting solutions showed no IR absorption due to coordinated DMC. The appearance of a band at 1755 cm^{-1} (in CH_3CN) or at 1742 cm^{-1} (in D_2O), due to the free carbonate, revealed that, under the working conditions, the complex decomposed fast by releasing coordinated DMC.

3.5. Coordination of DMC to Sc(III) and its relevance to the catalytic process [Eq. (1); R′ = Me, cat. = Sc(OTf)3]

3.5.1. Sc(OTf)3-catalyzed carbomethoxylation of $PhCH_2NH_2$: an IR study

To gain a deeper insight into the catalytic process [Eq. (1); R′ = Me, cat. = $Sc(OTf)_3$], the formation of $PhCH_2NHC(O)OMe$ from DMC and benzylamine, in CH_2Cl_2 and in the presence of the catalyst salt ($Sc(OTf)_3$), was monitored by IR spectroscopy.

$PhCH_2NHC(O)OMe$ (48.35 mg, 0.293 mmol) in CH_2Cl_2 (1.0 mL) solution shows characteristic IR absorptions at 3446 (ms, ν(NH)), 1723 (vs, ν(C=O)) and 1516 (s) cm^{-1}. Also the carbamate ester can η^1-O(C=O) coordinate to $Sc(OTf)_3$. As a matter of fact, the salt (88.60 mg, 0.180 mmol), poorly soluble in pure CH_2Cl_2, dissolved in a CH_2Cl_2 (4 mL) solution containing an excess of $PhCH_2NHC(O)OMe$ (184.40 mg, 1.12 mmol) and the IR spectrum of the resulting solution (carbamate/Sc: 6.2 mol/mol) showed, in addition to the bands of the free ester, new absorptions at 1683 (m), 1645 (s) and 1402 (ms) cm^{-1}, due to coordinated carbamate.[1]

Fig. 5 summarizes the results obtained when benzylamine and DMC were reacted, at 293 K, in CH_2Cl_2, in the presence of $Sc(OTf)_3$. Curve (a) (Fig. 5) shows the IR spectrum of a CH_2Cl_2 solution of DMC (0.35 M) and $Sc(OTf)_3$ (0.05 M). To a part (3.5 mL) of this solution benzylamine was added (Sc/amine/DMC: 1/3.5/7.2 mol/mol) and the IR spectrum of aliquots of the resulting reaction mixture recorded at different times. Spectrum (b) (Fig. 5), measured soon after (12 min) amine addition, clearly shows absorptions due to coordinated amine (≈ 3190 cm^{-1}) [54] and the product $PhCH_2NHC(O)OMe$ (3445, 1727 and 1514 cm^{-1}), whose intensities change (decrease and increase, respectively) during the run with the progress of the carbomethoxylation reaction (see (c) and (d) in Fig. 5). It is worth noting that no bands due to the carbamate ester $PhCH_2NHC(O)OMe$ were found in the IR spectrum of a CH_2Cl_2 (3.5 mL) solution of DMC (0.35 M) and the amine (0.595 mmol; DMC/amine: 2.1 mol/mol), even after a reaction time of 20 h at ambient temperature.

Marked spectral changes are observed also in the triflate region (1350–1000 cm^{-1}; spectra (b)–(d) in Fig. 5). In fact, as we have ascertained elsewhere [21,24], the starting catalyst modifies with time by reacting with amine and co-produced methanol and undergoes OMe/OTf exchange according to the reaction

$$x\mathrm{RNH_2} + \mathrm{L}_n\mathrm{Sc(OTf)}_3 + x\mathrm{CH_3OH} \rightarrow \mathrm{L}_n\mathrm{Sc(OCH_3)}_x\mathrm{(OTf)}_{3-x} + x\mathrm{(RNH_3)OTf}, \quad \mathrm{L} = \text{ligand}, \tag{4}$$

which also affords $(PhCH_2NH_3)OTf$, poorly soluble in CH_2Cl_2. Also the band originally located at 1645 cm^{-1} and assigned to coordinated DMC shifted upon addition of the amine and was replaced by a new absorption at 1661 cm^{-1}, which may be due, not only, to coordinated DMC, but, as supported by the presence of the band at 1404 cm^{-1} (spectra (b)–(d) in Fig. 5), also

[1] The presence of two bands due to O-coordinated C=O, such as those found at 1683 and 1645 cm^{-1}, has been also observed in the IR spectra of η^1-O(C=O)–Sc(III) complexes of carboxylic acid esters [38].

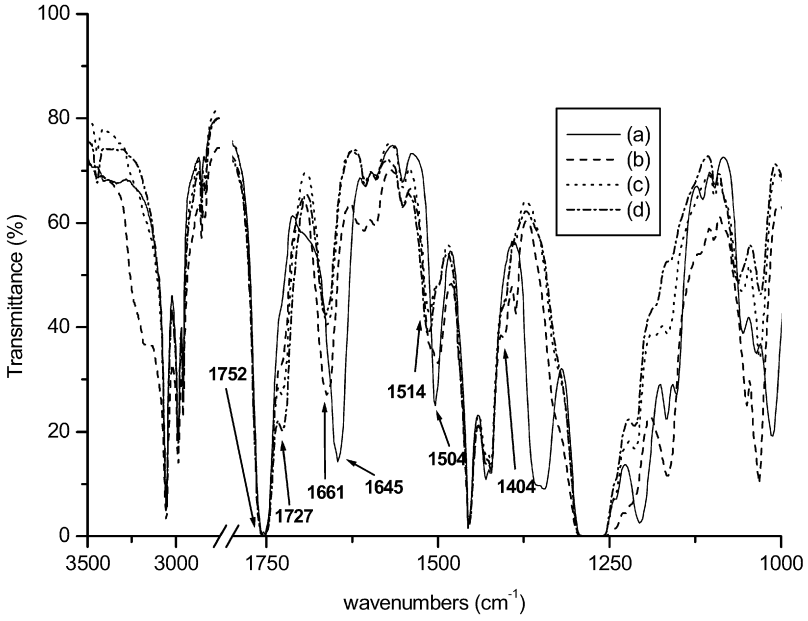


Fig. 5. (a) IR spectrum (3500–1000 cm^{-1}) of a stock solution of DMC (0.120 mL, 1.425 mmol) and $Sc(OTf)_3$ (97.25 mg, 0.198 mmol) in CH_2Cl_2 (4.0 mL); (b–d) IR spectra (3500–1000 cm^{-1}), measured at different times, of distinct aliquots (0.4 mL) of the reaction mixture obtained by adding $PhCH_2NH_2$ (0.066 mL, 0.604 mmol) to 3.5 mL of the stock solution; (b) spectrum measured after a reaction time of 12 min; (c) spectrum measured after a reaction time of 1 h; (d) spectrum measured after a reaction time of 4.5 h.

to coordinated carbamate ester. The above absorptions (1661 and 1404 cm^{-1}) disappeared after adding fresh amine (1 mmol) to the remaining reaction mixture. Under the latter conditions (excess of amine vs DMC), no bands assignable to coordinated C=O were visible in the spectrum (not reported in Fig. 5), but intense absorptions reappear around 3190 cm^{-1} revealing the presence, in solution, of coordinated amine [54].

The above data support the fact that the catalytic formation of carbamate ester [Eq. (1); R′ = Me, cat. = $Sc(OTf)_3$] is promoted by coordination of DMC to scandium (III) which effectively activates the substrate (DMC) even in the presence of potentially coordinating *N*-donor species (mono- and diamines [21,24]), at least when the carbomethoxylation reaction is carried out under the most usual conditions which employ an excess of DMC with respect to amine.

3.5.2. *Influence of O-donor species on the catalytic activity of $Sc(OTf)_3$*

If DMC coordination to Sc(III) is a process relevant to the catalytic reaction [Eq. (1); R′ = Me, cat. = $Sc(OTf)_3$], the presence in the reaction medium of species able to compete with DMC for the coordination sites on Sc(III) (THF, MeOH; see Section 3.2.1) must affect catalysis and is expected to hamper the catalytic activity of the Sc salt. We have, therefore, investigated, more closely, the influence of the presence of a few O-donors, such as THF and MeOH, on the catalytic activity of the salt.

In this study we have focused on benzylamine as reference amine. Fig. 6 compares the curves of formation of $PhCH_2NHC(O)OCH_3$ from DMC and benzylamine in the absence (curve (a)) and in the presence of O-donors species, such as THF (THF/Sc: 12.6 mol/mol; curve (b)) or MeOH (MeOH/Sc: 12.6 mol/mol; curve (c)). Curve (b) shows that

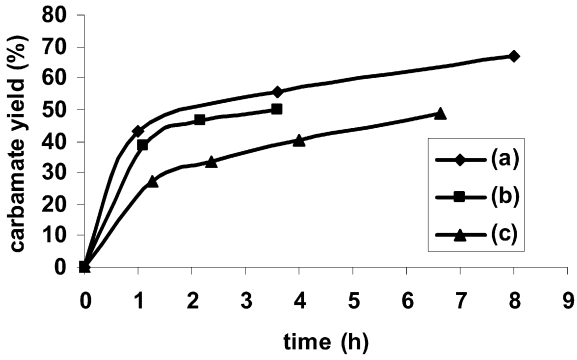


Fig. 6. Influence of O-donor species on the carbomethoxylation of $PhCH_2NH_2$ with DMC in the presence of $Sc(OTf)_3$ (293 K). (a) No O-donor was used. Sc/amine/DMC: 1/12.3/176 mol/mol. (b) O-donor: THF. Sc/amine/THF/DMC: 1/12.3/12.6/176 mol/mol. (c) O-donor: MeOH. Sc/amine/MeOH/DMC: 1/12.3/12.6/176 mol/mol.

addition of THF, in modest amounts (DMC/THF: 14 mol/mol) in order to avoid any significant dilution of the reaction mixture, has an inhibitory effect on the production of carbamate. The adverse effect was, obviously, still more notable when THF has been used as co-solvent in the catalytic process. Table 2, for instance, emphasizes that, in THF as co-solvent (DMC/THF = 1.5 v/v), under otherwise analogous reaction conditions, the $Sc(OTf)_3$-catalyzed carbomethoxylation of 1,6-diaminohexane [24] proceeds much more slowly (t_1 = 50 h) than in DMC (solventless conditions; t_1 = 24 h).

A much more marked inhibitory effect has been observed in the presence of MeOH (curve (c) in Fig. 6), which is not only an O-donor, but also a protic species. This is also due to the fact that methanol is involved, together with amine, in the modification of the salt [Eq. (4)], which, by losing OTf groups, converts

Table 2
Catalytic carbomethoxylation of 1,6-diaminohexane with DMC in the presence of $Sc(OTf)_3$ at 293 K

Entry	Diamine (mmol)	DMC (mL)	$Sc(OTf)_3$ (mmol)	THF (mL)	Sc/diamine/DMC/THF (mol/mol)	t_1[a] (h)	GC carbamate yield (%)	
							Monocarbamate	Dicarbamate
1[b]	13.6	3.0	0.36	–	1:38:100:0	24	18	75
2[b]	12.7	3.0	0.33	2	1:38:101:74	50	23	70

[a] Time required for the full conversion (100%) of the diamine.
[b] The carbomethoxylation reaction was very selective (≈ 100%). The observed products were dicarbamate $MeO(O)CNH(CH_2)_6NHC(O)OMe$, monocarbamate $H_2N(CH_2)_6NHC(O)OMe$ and the triflic salt $[MeO_2CNH(CH_2)_6NH_3]OTf$ [24].

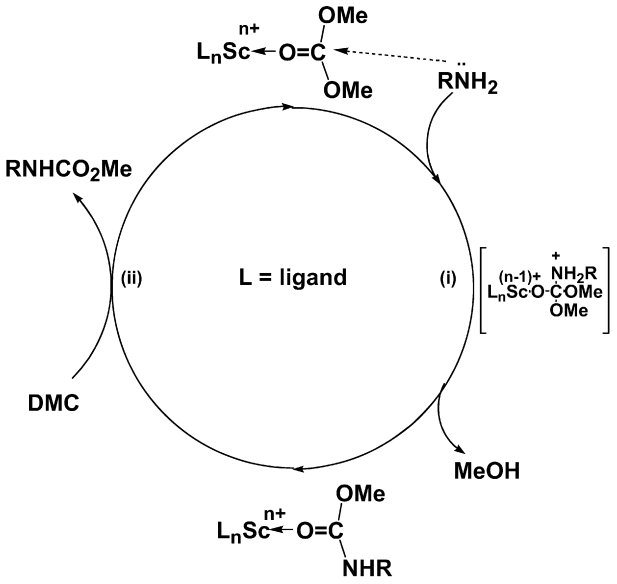
into catalytically less active Sc-methoxo species [21]. The incidence of reaction (4), which may be facilitated by the increased acidity of the alcohol upon coordination to the metal center [49,50], depends on the amount of methanol (vs Sc) present in the reaction medium and may affect heavily carbamate production since the early stages of the process, if, as in the case of run (c) in Fig. 6, a significant amount of MeOH (0.939 mmol) vs Sc (added MeOH/Sc: 12.6 mol/mol) is present in the reaction mixture at the beginning of the catalytic run. This finding helps to explain the reduced activity of catalytic system at high conversion (see also [21]), which cannot be ascribed merely to the coordinating properties of carbamate product and to its ability to compete with DMC for the coordination sites of scandium (III).

Also the presence of H_2O in the reaction mixture can markedly inhibit the catalytic activity of $Sc(OTf)_3$ (see [21]) and, consequently, the carbomethoxylation process [Eq. (1); $R' = Me$, cat. = $Sc(OTf)_3$] requires anhydrous conditions [21,24]. This fact clashes with the well known ability of $Sc(OTf)_3$ to work as water-tolerant Lewis acid catalyst in organic synthesis [55]. The results reported above (Sections 3.2.1 and 3.4) show that presence of water represses the coordinating ability of DMC toward $Sc(OTf)_3$ seriously. Moreover, as we have demonstrated elsewhere [21], the presence of water in the reaction medium can also cause, as a result of hydrolytic processes involving DMC and amine, the precipitation of poorly soluble metal-carbamato species [as established on the basis of their IR properties (3350–3340; 1570–1500; 1345–1340 cm^{-1}) and their behavior upon acidolysis with diluted HCl (evolution of CO_2)], with no or very poor catalytic activity under the working conditions.

3.6. DMC activation by $Sc(OTf)_3$: catalytic implications

Scheme 2 summarizes concisely a plausible reaction scheme for the $Sc(OTf)_3$-catalyzed carbomethoxylation of aliphatic amines with DMC [21,24]. The scheme fully accounts for the catalytic activity of the scandium salt, as the formation of carbamate ester is promoted by coordination of DMC to the metal center. This process, obviously, is still more facilitated under the solvent-free conditions we have usually employed for synthetic applications [21,24], wherein DMC itself was used as reaction medium in virtue of its ability to dissolve the catalyst ($ScOTf)_3$) and amine.

Our findings indicate that the behavior of $Sc(OTf)_3$ as carbomethoxylation catalyst differs somewhat from that described for $Zn(O_2CCH_3)_2{\cdot}2H_2O$ [22], whose catalytic activity is increased by the presence of an O-donor, such as methanol, in the reaction mixture. According to what reported in literature [22], coordination of methanol to Zn(II), by promoting the coordination change (bidentante to monodentate) of acetate ligand, facilitates the coordination of DMC to the metal center (Zn(II)) and enhances the catalytic activity of the zinc salt. The behaviors we have observed in a non-coordinating solvent, such as CH_2Cl_2 (Sections 3.2.1 and 3.3), and in neat DMC (Sections 2.6 and 3.4) clearly demonstrate, on the contrary, that coordination of DMC to $Sc(OTf)_3$ does not require any promoter. Moreover, as we have shown above, the presence of O-donors (methanol, THF, H_2O) hampers the coordination of the organic carbonate to Sc(III) (Section 3.2.1) and, in general, restrains the catalytic activity of the triflate salt (Section 3.5.2) significantly.



Scheme 2. Catalytic carbomethoxylation of aliphatic amines with DMC promoted by $Sc(OTf)_3$.

The interaction of the organic carbonate with Sc(III) induces a marked perturbation of the DMC molecule. The down field shift of ^{13}C carbonyl resonance indicates clearly that η^1-O(C=O) coordination of DMC to scandium ion enhances the electropositive character of carbonyl carbon atom [52]. Moreover, the negative shifts ($\Delta\nu = 35$ and 33 cm^{-1}, respectively) measured for $\nu_{asymm}(O–CH_3)$ and $\nu_{symm}(O–CH_3)$ modes of $(DMC)Sc(OTf)_3$ demonstrate also that η^1-O(C=O) coordination to the metal center weakens the $O–CH_3$ bonds

Table 3
Reaction of $PhCH_2NH_2$ or $PhNH_2$ with DMC at 363 K: catalytic effect of $Sc(OTf)_3$

Entry	R	RNH_2 (mmol)	DMC (mmol)	$Sc(OTf)_3$ (mmol)	Time (h)	Amine conversion (%)	GC yield (%)	
							$RNHCO_2Me$	$R(Me)NH + RNMe_2$
1[a]	$PhCH_2$	18.3	237	–	24	23[b]	13	3.5
2	$PhCH_2$	0.916	11.9	0.0737	1	70[c]	60	<1
3[a]	Ph	1	10.8	–	96	2	–	<2
4	Ph	0.82	9.03	0.0527	24	48	8	35

[a] The reaction was carried out in a 100 mL Schlenk tube (closed system).
[b] $(RNH_3)(O_2CNHR)$ (0.45 mmol, isolated) also formed (by reaction of RNH_2 with CO_2 generated through the methylation reactions [24]).
[c] Some $(RNH_3)OTf$ also formed.

of DMC. In principle, therefore, η^1-O(C=O) coordination of DMC to Sc(III) activates both the carbonyl group and the O–CH_3 moieties and, consequently, must enhance not only the carbomethoxylating but also the methylating reactivity of the substrate (DMC), which is, notoriously, a typical example of ambident electrophile [25]. An experimental evidence in support of this is presented in Table 3, which compares the effect of the scandium salt on the reactivity of DMC in the catalytic reaction with benzylamine and aniline, under otherwise analogous reaction conditions (temperature, Sc loading, etc.). In the presence of $Sc(OTf)_3$, DMC reacts with benzylamine to give the carbamate ester with high yield and selectivity (Entry 2 in Table 3). In the absence of the scandium salt, under comparable reaction conditions, the carbomethoxylation proceeds much more slowly with very low carbamate yield (Entry 1 in Table 3). The enhancement of methylating activity, under $Sc(OTf)_3$ catalysis, is documented by the reaction of DMC with an aromatic amine, such as aniline. As a matter of fact, aniline, which is poorly reactive toward DMC in the absence of any catalyst (Entry 3 in Table 3), at 363 K reacts with DMC in the presence of catalytic amounts of $Sc(OTf)_3$ to give preferentially *N*-methylation products (PhNMeH and $PhN(Me)_2$; Entry 4 in Table 3).

Table 3 also indicates that $Sc(OTf)_3$, as carbomethoxylation catalysts, is not so effective and selective for aromatic amines as for aliphatic ones. The lower electron density on the N-atom of aniline, due to lone-pair delocalization, can easily account for the lower reactivity of the aromatic amine with respect to aliphatic benzylamine. The full rationalization of the very different selectivities of the attacks by the two amines is, however, not so straightforward and, in principle, must consider, more closely, the interaction of each amine with both the electrophilic sites of the organic carbonate *coordinated to the metal center*. Here, we may note, in accordance with the HSAB theory [56], that the very high selectivity to carbamation observed with benzylamine (and other aliphatic amines as well) reflects the general tendency of "hard nucleophiles" (such as aliphatic amines) to react preferentially at a "harder" electrophilic center (such as the carbonyl group of the organic carbonate) rather than at a "softer" site (as the methyl groups are) [28,56]. However, the selectivity observed with aniline also indicates that the attack at the "soft" methyl groups may gain in importance when a less "hard" nucleophile, like aniline ("borderline nucleophile") [56], is used.

4. Conclusion

The role played by the metal center in the $Sc(OTf)_3$-catalyzed carbomethoxylation of aliphatic amines with DMC has been elucidated. The catalytic formation of carbamate ester is promoted by η^1-O(C=O) coordination of DMC to scandium. The ability of DMC to interact with $Sc(OTf)_3$ and coordinate to Sc(III) through the carbonyl oxygen atom has been demonstrated by spectroscopic methods (IR, NMR). A 1-to-1 (mol/mol) DMC–Sc(III) adduct, characterized as (η^1-O(C=O)–DMC)$Sc(OTf)_3$, has been also isolated for the first time and a relationship has been established between the coordination mode of DMC to Sc(III) and the reactivity of coordinated carbonate with amines. η^1-O(C=O) Coordination of DMC to Sc(III) results in the activation of both the carbonyl group and the O–CH_3 moieties of the organic carbonate and enhances not only the carbomethoxylating but also the methylating reactivity of the substrate (DMC), as supported by the different selectivity exhibited by the catalyst in the aminolysis of DMC with benzylamine and aniline.

Acknowledgments

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References

[1] M. Aresta, E. Quaranta, Chem. Tech. 27 (1997) 32.
[2] F. Porta, S. Cenini, M. Pizzotti, C. Crotti, Gazz. Chim. Ital. 115 (1985) 275.
[3] M. Aresta, C. Berloco, E. Quaranta, Tetrahedron 51 (1995) 8073.
[4] M. Aresta, A. Dibenedetto, E. Quaranta, Tetrahedron 54 (1998) 14145.
[5] M. Aresta, A. Dibenedetto, E. Quaranta, Green Chem. 1 (1999) 237.
[6] S. Carloni, D.E. De Vos, P.A. Jacobs, R. Maggi, G. Sartori, R. Sartorio, J. Catal. 205 (2002) 199.
[7] N. Yamazaki, F. Higashi, Int. Prog. Urethanes 2 (1980) 61.
[8] M. Pittelkow, R. Lewinski, J.B. Christensen, Synthesis 15 (2002) 2195.
[9] T. Yoshida, M. Sasaki, F. Hirata, Y. Kawanami, K. Inazu, A. Ishikawa, K. Murai, T. Echizen, T. Baba, Appl. Catal. A Gen. 269 (2005) 176.
[10] M. Distaso, E. Quaranta, J. Catal. 228 (2004) 36.
[11] H. Babad, A.G. Zeiler, Chem. Rev. 73 (1973) 75.
[12] D. Delledonne, F. Rivetti, U. Romano, Appl. Catal. A Gen. 221 (2001) 241.
[13] B. Orsat, P.B. Alper, W. Moree, C.-P. Mak, C.-H. Wong, J. Am. Chem. Soc. 118 (1996) 712.
[14] M.A.P.J. Hacking, F. van Rantwijk, R.A. Sheldon, J. Mol. Catal. B Enzym. 9 (2000) 201.
[15] T. Sima, S. Guo, F. Shi, Y. Deng, Tetrahedron Lett. 43 (2002) 8145.

[16] F. Mizia, F. Rivetti, U. Romano, US Patent 5 315 034 (1994), to EniChem Synthesis.
[17] Z.-H. Fu, Y. Ono, J. Mol. Catal. 91 (1994) 399.
[18] I. Vauthey, F. Valot, C. Gozzi, F. Fache, M. Lemaire, Tetrahedron Lett. 41 (2000) 6347.
[19] T. Baba, M. Fujiwara, A. Oosaku, A. Kobayashi, R.G. Deleon, Y. Ono, Appl. Catal. A Gen. 227 (2002) 1.
[20] M. Curini, F. Epifano, F. Maltese, O. Rosati, Tetrahedron Lett. 43 (2002) 4895.
[21] M. Distaso, E. Quaranta, Tetrahedron 60 (2004) 1531.
[22] T. Baba, A. Kobayashi, Y. Kawanami, K. Inazu, A. Ishikawa, T. Echizenn, K. Murai, S. Aso, M. Inomata, Green Chem. 7 (2005) 159.
[23] R.G. Deleon, A. Kobayashi, T. Yamauchi, J. Ooishi, T. Baba, M. Sasaki, F. Hiarata, Appl. Catal. A Gen. 225 (2002) 43.
[24] M. Distaso, E. Quaranta, Appl. Catal. B Environ. 66 (2006) 72.
[25] M. Aresta, E. Quaranta, Tetrahedron 47 (1991) 9489.
[26] M. Aresta, A. Dibenedetto, E. Quaranta, M. Boscolo, R. Larsson, J. Mol. Catal. A Chem. 174 (2001) 7.
[27] M. Selva, P. Tundo, A. Perosa, Tetrahedron Lett. 43 (2002) 1217.
[28] P. Tundo, L. Rossi, A. Loris, J. Org. Chem. 70 (2005) 2219.
[29] Y. Fu, T. Baba, Y. Ono, J. Catal. 197 (2001) 91.
[30] D.D. Perrin, W.L.F. Armarego, D.R. Perrin, Purification of Laboratory Chemicals, Pergamon, Oxford, 1986.
[31] S. Kobayashi, M. Sugiura, H. Kitagawa, W.W.-L. Lam, Chem. Rev. 102 (2002) 2227.
[32] H. Tsuruta, K. Yamaguchi, T. Imamoto, J. Chem. Soc. Chem. Commun. (1999) 1703.
[33] J.E. Katon, M.D. Cohen, Can. J. Chem. 53 (1975) 1378.
[34] M.F. Lappert, J. Chem. Soc. (1961) 817.
[35] M.F. Lappert, J. Chem. Soc. (1962) 542.
[36] M. Zackrisson, I. Linquist, J. Inorg. Nucl. Chem. 17 (1961) 69.
[37] W.L. Driessen, W.L. Groenevel, F.W. Van Der Wey, Rec. Trav. Chim. 89 (1970) 353.
[38] N.L. Chikina, Yu.V. Kolodazhnyi, O.A. Osipov, Zh. Obshch. Khim. 45 (1975) 1354.
[39] F. Kutek, Collect. Czech. Chem. Commun. 32 (1967) 3767.
[40] B. Dusek, F. Kutek, V. Kohout, Collect. Czech. Chem. Commun. 40 (1975) 2569.
[41] F. Bonino, A. Damin, S. Bordiga, M. Selva, P. Tundo, A. Zecchina, Angew. Chem. Int. Ed. 44 (2005) 4774.
[42] M. El M. Hamidi, J.-L. Pascal, Polyhedron 13 (1994) 1787.
[43] G.A. Lawrance, Chem. Rev. 86 (1986) 17.
[44] N.E. Dixon, G.A. Lawrance, P.A. Lay, A.M. Sargeson, Inorg. Chem. 23 (1984) 2940.
[45] D.H. Johnston, D.F. Shriver, Inorg. Chem. 32 (1993) 1045.
[46] V. Ripert, L.G.H. Pfalzgraf, J. Vaissermann, Polyhedron 18 (1999) 1845.
[47] K. Nakamoto, Infrared and Raman Spectra of Inorganic and Coordination Compounds, fourth ed., Wiley–Interscience, New York, 1986, p. 280.
[48] J.L. Atwood, K.D. Smith, J. Chem. Soc. Dalton Trans. (1974) 921.
[49] F. Kutek, B. Dusek, Collect. Czech. Chem. Commun. 35 (1970) 3768.
[50] C. Bisi Castellano, O. Carugo, A. Perotti, D. Sacchi, J. Mol. Catal. 85 (1993) 65.
[51] A. Abbasi, P. Lindqvist-Reis, L. Eriksson, D. Sandstrom, S. Lidin, I. Persson, M. Sandstrom, Chem. Eur. J. 11 (2005) 4065.
[52] J. Arai, K. Nishimura, Y. Muranaka, Y. Ito, J. Power Sources 68 (1997) 304.
[53] K. Matsubara, R. Kaneuchi, N. Maejita, J. Chem. Soc. Faraday Trans. 94 (1998) 3601.
[54] N.L. Firsova, Yu.V. Kolodazhnyi, O.A. Osipov, Zh. Obshch. Khim. 39 (1969) 2151.
[55] S. Kobayashi, Eur. J. Org. Chem. (1999) 15227.
[56] R.G. Pearson, J. Songstad, J. Am. Chem. Soc. 89 (1967) 1827.