

# Room temperature Baeyer–Villiger oxidation of cyclic and linear ketones using molecular oxygen, catalysed by a novel silica-supported nickel complex

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Letter

A nickel complex supported on a surface-functionalised silica gel is an active and selective heterogeneous catalyst for the liquid phase, room temperature Baeyer–Villiger oxidation of both cyclic and linear ketones using molecular oxygen.

The Baeyer–Villiger oxidation of cyclic ketones to lactones and linear ketones to esters is an important synthetic reaction. Although there are many reports of Baeyer–Villiger reactions using metal complexes in the literature, most of the work involves the use of peracetic acid, organic hydroperoxides or hydrogen peroxide as the source of oxygen.<sup>1</sup> The oxidation of cyclohexanone to  $\epsilon$ -caprolactone using molecular oxygen has been widely studied,<sup>2–8</sup> but activities and selectivities are generally disappointing and attempts to extend successfully the chemistry to include less facile substrates have typically met with little success. Furthermore, the reactions are often run for extended periods of time (usually 20–24 h) at elevated temperatures (typically 30–50 °C) and the catalysis itself often provides little enhancement over background oxidation. Use of a so-called sacrificial aldehyde as an oxygen transfer agent is a convenient and effective way of facilitating liquid phase oxidation reactions which employ molecular oxygen as the oxygen source.<sup>9–11</sup> The aldehyde is believed to act as an oxygen transfer agent *via* a radical mechanism<sup>12,13</sup> and forms the corresponding carboxylic acid as a potentially useful by-product. The effect of using different sacrificial aldehydes has been well documented and it is commonly reported that aromatic aldehydes (in particular benzaldehyde) favour the Baeyer–Villiger oxidation.<sup>14</sup>

A previous communication<sup>15</sup> demonstrated the versatility of a range of silica-supported metal complexes for a variety of oxidation reactions including the oxidation of alkylaromatic substrates and epoxidation of cyclohexane under mild conditions in the liquid phase. Here we report the startling activity of one such catalyst, containing nickel as the transition metal ion, in the Baeyer–Villiger oxidation of cyclic ketones to lactones and linear aryl ketonic side chains or linear ketones to the corresponding esters. Furthermore, the reactions are carried out under mild conditions, using molecular oxygen rather than peroxides and at room temperature and atmospheric pressure.

## Experimental

The preparation of the catalyst was carried out at room temperature. Silica with an average pore diameter of 100 Å (Keisegel 100) was suspended in ethanol. Trimethoxy-3-aminopropylsilane was added such that a ratio of 1.0 mmol silane (g silica)<sup>−1</sup> was obtained and the mixture was stirred for 24 h. The solid was then separated by filtration and washed thoroughly with diethyl ether to yield aminopropyl silica (AMPS). The AMPS was suspended in an excess of ethanol

and terephthaldialdehyde added at a ratio of 1 mmol (g silica)<sup>−1</sup>. The mixture was stirred for 2 h before being filtered and washed with diethyl ether. The resulting solid was then suspended in ethanol and *p*-aminobenzoic acid was added at a ratio of 1 mmol (g silica)<sup>−1</sup>. The mixture was stirred for *ca.* 24 h. The solid was again separated by filtration and washed with diethyl ether. The product was resuspended in ethanol and nickel acetate was added at a ratio of 1.0 mmol nickel (g silica)<sup>−1</sup> and the mixture stirred for 3 h. The excess of solvent was removed using a rotary evaporator and the catalyst thoroughly washed with ethanol until the washings were colourless. Finally, the catalyst was dried under vacuum at *ca.* 95 °C for 16 h. The proposed structure of the metal complex immobilised on silica is shown in Fig. 1.

The loading of nickel on the catalyst was determined by atomic absorption spectroscopy (AAS). The solid was first dissolved in concentrated sulfuric acid and the resulting solution diluted with deionised water. The loading was found to be 0.36 mmol g<sup>−1</sup>. Fourier transform infrared spectroscopy revealed a band at 1684 cm<sup>−1</sup> which is indicative of the imine group, as shown in the proposed structure of the catalyst (see Fig. 1). Bands at 1584 and 1456 cm<sup>−1</sup> were attributed to the antisymmetric and symmetric stretching modes of the carboxylate group respectively.

The Baeyer–Villiger reactions were carried out as follows. A reaction flask equipped with a reflux condenser and under an O<sub>2</sub> atmosphere was charged with 20.0 mmol of ketone, 60.0 mmol of benzaldehyde and 0.5 g of catalyst (*i.e.* 0.18 mmol active sites). A range of different solvents were used for the reactions (120 mL). The reactions were carried out at room temperature (*ca.* 16–18 °C), with constant stirring using a magnetic stirrer. Samples were withdrawn at regular intervals and analysed by gas chromatography. A control reaction was carried out in exactly the same way but with the omission of the catalyst.

## Results

Fig. 2 shows the reaction profiles for the selective oxidation of cyclohexanone to  $\epsilon$ -caprolactone using benzene as the solvent.

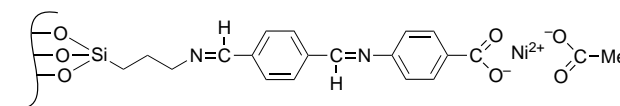


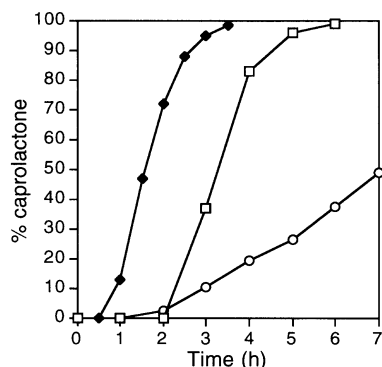
Fig. 1 Proposed structure of the nickel complex immobilised on silica

**Table 1** Baeyer–Villiger oxidation of ketones using an immobilised nickel catalyst in the presence of molecular oxygen and benzaldehyde<sup>a</sup>

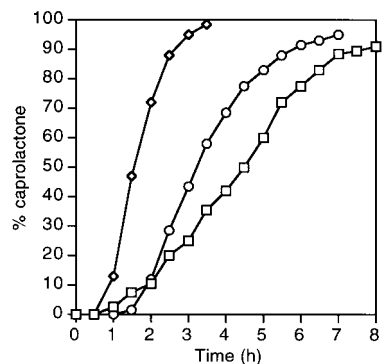
Substrate	Solvent	Time/h	Product <sup>b</sup>	GC Yield (%)	Turnover <sup>c</sup>
Cyclohexanone	C <sub>6</sub> H <sub>6</sub>	3.5	$\epsilon$ -Caprolactone	98	49
Cyclohexanone	CH <sub>2</sub> Cl <sub>2</sub>	7	$\epsilon$ -Caprolactone	95	34
Cyclohexanone	CH <sub>2</sub> ClCH <sub>2</sub> Cl	8	$\epsilon$ -Caprolactone	91	20
Cyclohexanone	PhMe	24	$\epsilon$ -Caprolactone	15	0.7
Cyclopentanone	C <sub>6</sub> H <sub>6</sub>	7	Valerolactone	91	31
<i>p</i> -Methoxyacetophenone	C <sub>6</sub> H <sub>6</sub>	24	<i>p</i> -Methoxyphenyl acetate	81	3.8
Pinacolone	C <sub>6</sub> H <sub>6</sub>	24	<i>t</i> -Butyl acetate	76	3.5

<sup>a</sup> Reaction conditions: catalyst 0.5 g, substrate 20 mmol, benzaldehyde 60 mmol, solvent 120 mL, 16–18 °C. <sup>b</sup> As confirmed by GC–MS.

<sup>c</sup> Turnover number per h per catalytic site.

**Fig. 2** Percentage conversion of cyclohexanone to  $\epsilon$ -caprolactone with no catalyst (○), catalyst activated at 105 °C for 24 h (◆) and catalyst used without activation (□)

A significant rate enhancement is observed using the immobilised nickel catalyst, with a maximum rate of up to 44% h<sup>-1</sup> (equivalent to 49 turnover h<sup>-1</sup> per catalytic site) and a yield of 98% (GC) using the activated catalyst (Table 1). Catalyst activation at 105 °C for 24 h successfully removed the induction period. A significant solvent effect is observed in this reaction, with a maximum rate of 44% h<sup>-1</sup> in benzene, 31% h<sup>-1</sup> in dichloromethane and 18% h<sup>-1</sup> in 1,2-dichloroethane (Fig. 3). Yields and turnover numbers for these reactions are presented in Table 1. No conversion was observed after 7 h using toluene as the solvent, although a yield of 15% was obtained after 24 h (*i.e.* an average of 0.7 turnover h<sup>-1</sup> per catalytic site). The induction period was also found to vary remarkably with solvent. The catalyst has also been used to oxidise other cyclic ketones using benzene as the reaction solvent under the same conditions. Cyclopentanone is selectively oxidised to valerolactone at a rate of up to 28% h<sup>-1</sup> (equivalent to 31 turnover h<sup>-1</sup> per catalytic site) in a yield of *ca.* 91%.

**Fig. 3** Percentage conversion of cyclohexanone to  $\epsilon$ -caprolactone by supported Ni catalyst using benzene (◇), dichloromethane (○) and 1,2-dichloroethane (□) as the solvent

Reports of the Baeyer–Villiger oxidation of linear aliphatic ketones and aromatic side chains using molecular oxygen are scarce in the literature.<sup>5</sup> The immobilised nickel catalyst described here is effective for such oxidations. For example, *p*-methoxyacetophenone is oxidised to *p*-methoxyphenyl acetate in 81% yield in 24 h (*i.e.* an average of 3.8 turnover h<sup>-1</sup> per catalytic site) and pinacolone is oxidised to *t*-butyl acetate in 76% yield after 24 h (*i.e.* an average of 3.5 turnover h<sup>-1</sup> per catalytic site, Table 1). In all cases the reactions exhibit high selectivity, with only trace amounts of by-products detected by GC.

Further studies are in progress to rationalise the solvent effects in these reactions, to determine the effect of reaction temperature and to investigate catalyst reuse.

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