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Formation of ε-caprolactam via catalytic Beckmann rearrangement using P_2O_5 in ionic liquids

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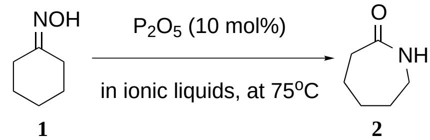
Abstract—Catalytic Beckmann rearrangement of cyclohexanone oxime in ionic liquids using P_2O_5 or Eaton's reagent has been investigated. 1-*n*-Butyl-3-methylimidazolium hexafluorophosphate ($bmiPF_6$) gives superior results to those noted by earlier workers. © 2001 Elsevier Science Ltd. All rights reserved.

Recent exploration of industrial potential of green chemistry using room-temperature ionic liquids, particularly those based on 1,3-dialkylimidazolium cations such as 1-*n*-butyl-3-methylimidazolium tetrafluoroborate ($bmiBF_4$) and 1-*n*-butyl-3-methylimidazolium hexafluorophosphate ($bmiPF_6$), as novel reaction media has become an exciting area of research. Their utility in alkylation, acylation, hydrogenation, Diels–Alder and Heck reactions as well as other organic transformations has been demonstrated.[1]

The rearrangement of a ketoxime to the corresponding amide is a powerful method in organic synthesis and is know as the Beckmann rearrangement,[2] particularly for manufacturing of ε-caprolactam in chemical industry. This reaction, however, generally requires high reaction temperature (approximately 130°C) and large amount of strong Brønsted acid such as sulfuric acid, phosphorous pentachloride in ether, or hydrogen chloride in a mixture of acetic acid and acetic anhydride in a non catalytic fashion. The use of excessive amount of these chemical reagents/solvents can lead to large amount of by-products, causing serious corrosion problems.[3] Vapor-phase Beckmann rearrangement processes at high reaction temperature results in low selectivity for ε-caprolactam.[4] Recently the Beckmann rearrangement in supercritical water has been reported.[5] Beckmann rearrangement catalyzed by the combined use of tetrabutylammonium perrhenate(VII) and trifluoromethanesulfonic acid has been studied.[6] Arisawa and Yamaguchi found that a small amount of rhodium complex could promote the reaction of ketoxime and trifluoromethanesulfonic acid.[7]

The rate-determining step in a Beckmann rearrangement is known to be the partial ionization of the nitrogen–oxygen bond of the oxime followed by the formation of cyclic iminium intermediate.[3] It is reasoned that such positively charged intermediate should be stabilized by the ionic liquid media. It is also believed that the acidity of Brønsted acids is enhanced in ionic liquids because of the lack of solvation of proton. These factors should in turn facilitate the Beckmann rearrangement, perhaps at much lowered reaction temperature (Scheme 1). Most recently, a new approach based on 1,3-dialkylimidazolium or *N*-alkylpyridinium salts and 10–20 mol% of PCl_5 as media for the Beckmann rearrangement of several oximes was reported by Deng et al.[8] When catalytic amount (20 mol%) of phosphorous pentoxide (P_2O_5) was used in ionic liquid $bmiBF_4$, conversion to ε-caprolactam was low (32%), and hydrolysis to cyclohexanone reached to 66%.

We were interested in examining the utility of room temperature ionic liquids, for example, $bmiBF_4$ and $bmiPF_6$,[9] as reaction media for Beckmann rearrange-



1 2

Scheme 1.

Keywords: ε-caprolactam; cyclohexanone oxime; phosphorous pentoxide; ionic liquids.

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Table 1. Catalyzed Beckmann rearrangement of cyclohexanone oxime (**1** to ε-caprolactam **2** in ionic liquids via Scheme 1)

Entry	Ionic liquid	Catalyst[a]	*T* (°C)	*t* (h)	Yield (%)[c]
1	$bmiPF_6$	P_2O_5	75	16	95
2	$bmiPF_6$	P_2O_5	95	21	95
3	$bmiPF_6$	Eaton's reagent	75	21	99
4	$bmiPF_6$	Eaton's reagent	95	24	99
5	$bmiBF_4$	P_2O_5	95	16	–[d]
6	$bmiBF_4$	Eaton's reagent	75	21	–[d]
7	$bmiBF_4$	Eaton's reagent[b]	75	16	66[d]

Note: All reactions were all carried out in sealed vial at 2 M concentration at room temperature for 16–24 h in 1 ml of $bmiBF_4$ or $bmiPF_6$, monitored via GC/MS.

[a] Catalyst loading: 10 mol% P_2O_5 and 10 mol% Eaton's reagent unless otherwise indicated.

[b] 20 mol%.

[c] Yields are based on GC/MS.

[d] Presumably due to higher content of water in $bmiBF_4$.

ment of cyclohexanone oxime, preferring the use of P_2O_5 as PCl_5 will inevitably produce volatile hydrogen chloride by-product. Nevertheless, when the proposed Beckmann rearrangement was carried out using 95% sulfuric acid and 85% phosphoric acid at elevated temperature (75–95°C) in ionic liquids ($bmiBF_4$ or $bmiPF_6$), all reaction failed and only cyclohexanone was observed as the hydrolytic product of oxime. The presence of water may also have reduced the acidity of proton through solvation.

We then decided to use P_2O_5 or Eaton's reagent (7.7% P_2O_5 in methanesulfonic acid) which should in principle create a vigorously anhydrous reaction media so as to minimize the competitive hydrolysis of oxime. The acidity of phosphoric acid (derived from P_2O_5 and the moisture contained in the starting material and ionic liquids) and methanesulfonic acid should also be much enhanced. When P_2O_5 was used as the catalyst in $bmiPF_6$, cyclohexanone oxime **1** was smoothly transformed to ε-caprolactam **2** in high yield (Table 1, entry 1) at temperature just above 75°C. Raising the reaction temperature (for example to 95°C) and lengthening reaction time did not offer significant advantages (entry 2). When Eaton's reagent was used, similar results were observed (entries 3 and 4).[10] The use of $bmiBF_4$ as reaction media gave erratic results (entries 5–7) and in some cases the hydrolysis of oxime back to cyclohexanone was observed.[11] This is probably attributed to the more water-miscible nature of $bmiBF_4$ ionic liquid, which may be harder to dry than $bmiPF_6$. In entry 7, when $bmiBF_4$ ionic liquid was extensively dried azeotropically using toluene (three times), 66% yield for the Beckmann rearrangement was achieved. It thus appears that vigorously dried ionic liquids are essential for the success of such Beckmann rearrangement catalyzed by P_2O_5. Hence, $bmiPF_6$, due to its water-immiscible nature to some extent, may be a better choice for this reaction because removal of water should be easier. The isolation of product can be achieved through distillation under reduced pressure or application of the known procedure of using methylene chloride as extractant.[8]

We next examined the possibility of one-pot Beckmann rearrangement to ε-caprolactam from cyclohexanone oxime formed from mixing cyclohexanone and hydroxylamine (or its salts) in ionic liquids. Thus, 1 equiv. of hydroxylamine hydrogen chloride and 1 equiv. sodium acetate[12] were mixed with cyclohexanone in $bmiPF_6$ at 40°C overnight to give cyclohexanone oxime. Upon addition of catalytic amount of Eaton's reagent and heating up to 75°C, Beckmann rearrangement proceeded albeit incompletely. It was observed that the oxime was partially hydrolyzed[13] back to cyclohexanone starting material. To circumvent this problem it is desirable that the formation of oxime be conducted separately.[14]

In conclusion, catalytic Beckmann rearrangement of cyclohexanone oxime using catalytic amount of P_2O_5 or Eaton's reagent has been successfully carried out in $bmiPF_6$. This ionic liquid facilitated such reaction at much lowered reaction temperature with excellent conversion.

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