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[2,3]-Sigmatropic rearrangement of propargylic sulfinates by a Pale Cu^I-USY zeolite and copper salts

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ABSTRACT

The sigmatropic rearrangement of propargylic sulfinates to allenic sulfones is catalyzed by the copper cation. The Pale Cu^I-USY zeolite, as well as copper salts, lead to essentially quantitative yield of the corresponding allenic sulfones.

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A class of compounds known as allenic sulfones is important in organic synthesis.¹ They participate in many types of processes including a plethora of cycloadditions and cyclization reactions.² Our interest in multiple areas employing allenic sulfones as precursors has led us to further examine their preparation.

In the early 1960s, the Boisselle and Pudovik groups reported the thermal [2,3]-sigmatropic rearrangement of propargyl esters of phosphonous acid to allenic phosphorus compounds.³ Shortly thereafter, the Braverman and Stirling groups both reported the thermal [2,3]-sigmatropic rearrangement of propargylic sulfinates to allenic sulfones.⁴ This rearrangement was determined to proceed through a cyclic intramolecular mechanism. In the years since the first report of these rearrangements, the conversion of sulfinate esters to allenic sulfones has also been catalyzed by rhodium,⁵ palladium,⁶ and silver species.⁷

In 2008, we reported the [2,3]-sigmatropic rearrangement of propargylic sulfinates to allenic sulfones catalyzed by silver hexafluoroantimonate (eq. 1).^{7b} We have also recently studied the effect of other silver salts on this process. It was observed that silver salts in which the anion was strongly noncoordinating, the rearrangement was rapid and resulted in high yields of the corresponding allenic sulfone. In addition, we

examined the ability of a silver-doped ultrastable Y (USY) faujasite zeolite prepared by the Pale group to effect this rearrangement and found that this recoverable heterogeneous catalyst was efficient in producing the rearrangement products.⁸

As an extension of our work studying this rearrangement of propargylic sulfinates, we expanded to the use of copper to catalyze this transformation. The Pale group has pioneered the use of heterogeneous copper-doped zeolites in the areas of cycloadditions and homocoupling,⁹ but they have no reported use as yet to catalyze [2,3]-sigmatropic rearrangements.

We initially began our studies of the Cu^I-USY zeolite-catalyzed rearrangement with an examination of solvent media. In general, the propargylic sulfinate was dissolved in solvent and catalyst was added at room temperature. The reaction was monitored by TLC. Upon completion, or 7 days, whichever came first, the reaction mixture was filtered through a nylon membrane to recover zeolite and the solvent was removed. The products were pure (or pure mixtures) and yields could be determined accordingly. The nylon membrane was dried for 20 minutes by flowing air (i.e., vacuum was maintained after filtration). No attempt was made to determine the copper content after using the catalyst. It was observed that the reaction proceeded most rapidly in dichloromethane followed closely by nitroethane (Table 1, entries 1 & 7). This is consistent with our previous reports of the silver-catalyzed reaction.^{7b} All other solvents examined were less effective media for the rearrangement, resulting in recovery of starting material even after a one-week reaction time (Table 1). As a result,

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dichloromethane was used as the solvent for the remainder of the optimization studies.

We next examined the effect of catalyst loading on the reaction duration and yield. The Cu^I-USY zeolite was prepared by cation exchange by the Pale group and determined to contain 2.6 mmol Cu⁺ per gram of zeolite.^{9b} Therefore, the catalyst loading percentages are based on molar equivalents of Cu⁺ cation employed in the reaction. It was observed that when the rearrangement was run side-by-side with different catalyst loadings that the reaction appeared to occur at the same rate by thin layer chromatography monitoring and all reactions were completed within 25 hours (Table 2). The increased loading of Cu⁺ did not accelerate the rate of reaction significantly.

Table 1. Effects of solvent on the Cu^I-USY zeolite-catalyzed rearrangement.

Entry	Solvent	Time	Catalyst Recovered (%) ^(a)	Yield (%)
1	CH ₂ Cl ₂	25 h	71	100
2	THF	7 d	85	100
3	Toluene	7 d	100	67 ^(b)
4	Et ₂ O	7 d	83	84 ^(c)
5	ClCH ₂ CH ₂ Cl	7 d	75	75 ^(d)
6	MeCN	7 d	76	96
7	EtNO ₂	68 h	100	94 ^(e)
8	EtOAc	68 h	85	98 ^(f)

^(a) The recovered catalyst was scraped from the nylon membrane before weighing, rather than determining the difference of the membrane with and without recovered catalyst. Therefore, observed recovery is lower than actual recovery due to adherence of particles to the membrane. ^(b) Recovered 33% of **3**. ^(c) Recovered 8% of **3**. ^(d) Recovered 7% of **3**. ^(e) Recovered 6% of **3**. ^(f) Recovered 2% of **3**.

Table 2. Catalyst loading effects of Cu^I-USY zeolite-catalyzed rearrangement.

Entry	Catalyst Loading (mol%)	Time	Catalyst Recovered (%) ^(a)	Yield (%)
1	10	25 h	71	100
2	15	25 h	95	100
3	17.5	25 h	69	94
4	20	25 h	95	88

^(a) The recovered catalyst was scraped from the nylon membrane before weighing, rather than determining the difference of the membrane with and without recovered catalyst. Therefore, observed recovery is lower than actual recovery due to adherence of particles to the membrane.

As the Cu-doped zeolite is a heterogeneous catalyst, it can be easily recovered from the reaction by simple filtration over a nylon membrane and then used to catalyze another reaction. We examined this cursorily and found that the catalyst was able to be

used at least three times without any notable decline in yield of the allenic sulfone, but that the reaction time grew slightly longer with each reuse (Table 3).

The ability of Cu^I-USY to catalyze the [2,3]-sigmatropic rearrangement was not limited to the *p*-toluenesulfonyl allenic sulfone. As shown in Table 4, a small number of propargylic sulfinates were also converted to their allenic counterparts. The more sterically hindered sulfinates such as the naphthalene and the 2,4,6-tri-*iso*-propylbenzene derivatives required about one week to complete the rearrangement, but still resulted in high yields (Table 4, entries 2-3). The simple phenyl system and cyclohexyl derivative were completed within 2-3 days at room temperature (Table 4, entries 1 and 4).

Table 3. Successive reuse of Cu^I-USY zeolite.

Entry	Catalyst	Time (h)	Catalyst Recovered (%) ^(a)	Yield (%)
1	Run 1	28 h	90	89
2	Run 2	33 h	89	95
3	Run 3	42 h	90	91

^(a) Recovered catalyst determined by difference of nylon membrane mass with and without zeolite recovered

Table 4. Cu^I-USY catalyzed rearrangement of propargylic sulfinates.

Entry	Ar	R ₁ /R ₂	Time (h)	Catalyst Recovered (%) ^(a)	Yield (%)
1	Ph	Me/Me	48 h	96	87
2	2-Naph	Me/Me	8 d	100	95
3	Tris ^(b)	Me/Me	8 d	88	96
4	<i>p</i> Tol	-(CH ₂) ₅ -	3 d	96	93

^(a) Recovered catalyst determined by difference of nylon membrane mass with and without zeolite recovered. ^(b) Tris = 2, 4, 6-tri-*iso*-propylbenzene.

After completing an examination of the ability of the copper-doped zeolite, Cu^I-USY, to catalyze the [2,3]-sigmatropic rearrangement of propargylic sulfinates, we elected to investigate the effectiveness of other copper salts, both copper (I) and copper (II), on the rearrangement reaction. The results are shown in Table 5. The reactions were monitored by TLC until complete conversion of sulfinate ester to allenic sulfone or a one-week reaction time, whichever was shorter. Copper halides were able to induce the rearrangement with qualitative reaction rates in the order of chloride > bromide > iodide (Table 5, entries 2-4). Copper (II) salts were also able to induce the sigmatropic rearrangement, strongly noncoordinating anions resulting in qualitatively faster reaction times. The least effective salts were copper (II) acetate and copper (II) nitrate, which afforded mostly starting material after a one-week reaction time. In one case with copper (I) thiophene-2-carboxylate, a terminal coupling product **7** was isolated as the major product (Table 5, entry 1). In an endeavor to improve the copper salt-catalyzed reactions,

dichloromethane was replaced with nitroethane and the rearrangement was tried with three copper salts. The yields were also excellent and in each case the rate of reaction was increased, indicating that nitroethane is also an excellent medium for the copper salt-catalyzed sigmatropic rearrangement of propargylic sulfinates to allenic sulfones (Table 5, entries 14-16).

The reactivity of the copper-doped zeolite is not as high as the silver catalysts. It takes a significantly longer time to complete the desired rearrangement. However, copper is a much more abundant element and markedly less expensive than silver-based reagents, which are both key factors in deciding what catalyst to use to induce the desired reactions.

Table 5. [2,3]-Sigmatropic rearrangement via copper salts.

Entry	CuX _n in CH ₂ Cl ₂ (10 mol %)	Time	Yield (%)
1	CuTC ^(a)	1 h	100 ^(b)
2	CuCl	46 h	83
3	CuBr	70 h	99
4	CuI	7 d	86 ^(c)
5	CuCN	7 d	85 ^(d)
6	CuCl ₂	68 h	96
7	Cu(BF ₄) ₂	93 h	99
8	Cu(CO ₂ CF ₃) ₂	5 d 4 h	91
9	Cu(ClO ₄) ₂	6 d	97
10	Cu ₂ O	7 d	^(e)
11	Cu(OAc) ₂	7 d	^(f)
12	CuSO ₄	7 d	^(g)
13	Cu(NO ₃) ₂	7 d	^(h)
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	CuX _n in EtNO ₂		
14	CuCl	40 h	90
15	Cu(BF ₄) ₂	24 h	97
16	Cu(CO ₂ CF ₃) ₂	52 h	93

^(a) CuTC = Copper (I) thiophene-2-carboxylate. ^(b) Coupling product **7** isolated as major product 1.0:0.1, **7:4**. ^(c) A mixture of **4:3** was isolated in a ratio of 1.0:0.1. ^(d) A mixture of **4:3** was isolated in a ratio of 0.65:1.0. ^(e) A mixture of **4:3:7** was isolated in a ratio of 1.0:0.1:0.07. ^(f) A mixture of **4:3:7** was isolated in a ratio of 0.2:1.0:0.08. ^(g) A mixture of **4:3** was isolated in a ratio of 1.0:1.2. ^(h) A mixture of **4:3** was isolated in a ratio of 0.25:1.0.

We have now demonstrated that copper ions can also be utilized as a catalyst for the [2,3]-sigmatropic rearrangement of propargylic sulfinates to allenic sulfones. The copper cation can either be simple homogeneous copper (I) or (II) salts or can be a copper-doped heterogeneous USY zeolite catalyst. The transformation is less rapid with copper catalysis than silver catalysis, but the use of copper instead of silver and using a recoverable catalyst makes the process more “green.” The

development of the rearrangement reaction and further applications of allenic sulfones is currently underway and results will be reported in due course.

Experimental Section

General procedure. The propargylic sulfinate was dissolved in the solvent (0.05 M). The copper catalyst was added in one portion. The mixture was stirred at room temperature and the reaction was monitored by TLC. Upon complete conversion to the product (or one week reaction time), the catalyst was removed by filtration (using a Sterilite nylon membrane (0.2 μm, 47 mm) for the zeolite catalyst, or through a short pad of Celite for the copper salts) and rinsed with dichloromethane. The zeolite catalyst was dried by aspiration and then recovered by carefully scraping it from the membrane; traces remain adsorbed to the membrane and prevent complete recovery. The filtrate was concentrated on a rotary evaporator and trace solvent removed by high vacuum pump to yield the allenic sulfone.

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