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A polystyrene-supported triflating reagent for the synthesis of aryl triflates

Cecilia Wan Ying Chung and Patrick H. Toy*

\[
\begin{align*}
\text{Ar} & \xrightarrow{NHTf} \text{ArOTf} \\
\text{ArNH}_2 & \xrightarrow{\text{ArOH, base}} NHTf + \text{ArOTf}
\end{align*}
\]
A polystyrene-supported triflating reagent for the synthesis of aryl triflates

Cecilia Wan Ying Chung and Patrick H. Toy*

Department of Chemistry, The University of Hong Kong, Pokfulam Road, Hong Kong, People’s Republic of China

Abstract—An insoluble polystyrene-supported triflating reagent has been prepared by suspension co-polymerization of N-(4-vinylphenyl)trifluoromethanesulphonimide, styrene and the Janda/el® cross-linker. This reagent, in the presence of triethylamine, allows for the efficient synthesis of aryl triflates from a wide range of phenols in a process that permits the desired product to be isolated from the reaction mixture in essentially pure form via several filtration and concentration operations. Adding to the utility of this reagent is its ability to be easily recovered, regenerated and reused. Both soluble and insoluble bifunctional polymers containing trialkylamine moieties in addition to triflimide groups were also prepared and examined as triflating reagents. Unfortunately these reagents afforded only modest yields of the desired products in representative reactions. © 2004 Elsevier Science. All rights reserved

1. Introduction

The use of polymer-supported reagents and catalysts in polymer-assisted organic synthesis has become commonplace since they can reduce product purification to simple filtration and concentration operations and are potentially easily recycled.1 A vast array of such reagents and catalysts have been reported that use both insoluble2 and soluble3 polymers as their carriers and new ones are continually being developed in order to broaden the range of reactions in which they are applicable. In this regard, we have a long-standing interest in the development of both soluble and insoluble polymer-supported amine,4 fluorinated ketone,5 phosphine,6 sulfide7 and sulfoxide8 reagents. Thus, in our research we have noticed that a missing tool from the polymeric reagent toolbox is a readily accessible and easy to use heterogeneous polymer-supported reagent that allows for the conversion of phenols to aryl triflates and isolation of the products via simple filtration and concentration operations.

Aryl triflates are versatile building blocks in organic synthesis since they participate in a variety of metal catalyzed carbonylation and coupling reactions9,10. Thus, methods and reagents for the synthesis of aryl (an enol) triflates are constantly being developed and refined.

Recent developments for their preparation include the use of triflic anhydride in an aqueous biphasic reaction system,11 and the use of N-phenyltrifluoromethanesulphonimide (1)12 (Figure 1) in conjunction with controlled microwave heating.13 One drawback associated with the use of reagent 1 is that it and its by-products can be difficult to separate from the triflate product. Therefore both polar analog 2, which not only aids in product purification but also accelerates its formation,14 and soluble poly(ethylene glycol)-supported analog 3,15 which can facilitate product isolation, have been reported. While the former has seen widespread use, the latter has not. Perhaps one reason for the lack of use of 3 is that it requires a precipitation operation before it and its by-products can be removed by filtration, and thus, it is not very amenable to use in parallel synthesis or with automation equipment. Therefore an insoluble polymer-supported reagent that does not require a precipitation step prior to filtration might find broader acceptance and utilization. Herein we wish to report the synthesis and use of such a reagent.
2. Results and Discussion

The preparation of a polymer-supported triflating reagent requires an aniline polymer as the base material and many preparations of such polymers have been reported. These methods include Schmidt rearrangement of a benzyl azide resin, attachment of an aniline derivative to a preformed polymer, and the incorporation of either 4-vinylaniline or N-Boc-4-vinylaniline in the polymerization process. While any of these methods could have provided us with a suitable polymeric starting material, we choose a more direct route by preparing a functional monomer containing the desired triflimide functional group and incorporating it into the polymer during the polymerization process.

Thus functional monomer 4 was prepared in 90% yield by reaction of 4-vinylaniline with 2 equivalents of Tf₂O in the presence of excess Et₃N. After determining the stability of 4 to the polymerization reaction conditions, it was used to prepare an insoluble polystyrene reagent. Thus it was suspension co-polymerized with styrene and the flexible Janda/El® cross-linker to afford insoluble 5 (Janda/El®-NTf₂) (Scheme 1). Elemental analysis was used to determine the loading level of 5 to be 1.6 mmol NTf₂ g⁻¹ based on the average analysis results for nitrogen and sulphur content.

Next we examined the use of 5 in the preparation of a variety of aryl triflates derived from phenols (6a-i) substituted with both electron donating and withdrawing substituents (Table 1). These reactions were performed in dichloromethane at room temperature using 2 equivalents of both 5 and Et₃N. Upon the complete disappearance of 6a-i according to TLC analysis (4-16 h), the reactions were filtered to remove the insoluble polymer, concentrated in vacuo and filtered through a short plug of silica gel. Finally, removal of the solvent afforded triflates 7a-i in essentially pure form, as determined by ¹H NMR analysis. As can be seen in Table 1, all substrates were isolated in good to excellent yield.

Table 1. Aryl triflate synthesis.

<table>
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<tr>
<th>Phenol</th>
<th>Triflate</th>
<th>Yield (%)</th>
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<tbody>
<tr>
<td>ArOH</td>
<td>5, Et₃N</td>
<td>ArOTf + NHTf</td>
</tr>
<tr>
<td>6a-i</td>
<td>7a-i</td>
<td>8</td>
</tr>
</tbody>
</table>

Scheme 1. Synthesis of reagents 5. Reagents and conditions: (a) Et₃N (3 eq), Tf₂O (2 eq), anhydrous CH₂Cl₂, 0 °C. (b) PhCl, AIBN, water, acacia gum, NaCl, 85 °C.
With our success in synthesizing aryl triflates containing carbonyl functional groups (7h-i), we were interested to see if aryl triflates containing aliphatic alcohols could also be prepared. Gratifyingly, diols 6j-l afforded the corresponding monotriflates 7j-l in moderate to good yield (Table 2) when the reactions were performed at 50 °C. The structures of 7j-k were confirmed by their oxidation to the corresponding aldehyde and ketone (7h), respectively. It should be noted that these reactions were quite sluggish even at elevated temperature and 2-5 days and 4 equivalents of 5 were required for the complete consumption of the starting diol. Furthermore, the formation of 7j-l was accompanied by numerous uncharacterized impurities and these products required chromatographic purification. One possible explanation for the requirement of a larger excess of 5 for the synthesis of 7j-l is that the isolated products may have been formed by hydrolysis of initially generated ditriflate molecules. Such a reaction pathway would also explain the complex crude product mixtures obtained for 7j-l.

Table 2. Synthesis of aryl triflates containing aliphatic alcohol groups.

<table>
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<tr>
<th>Phenol</th>
<th>Triflate</th>
<th>Yield (%)</th>
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<tbody>
<tr>
<td>OH</td>
<td>HO</td>
<td>48</td>
</tr>
<tr>
<td>HO</td>
<td>HO</td>
<td>90</td>
</tr>
<tr>
<td>HO</td>
<td>HO</td>
<td>63</td>
</tr>
</tbody>
</table>

Having established that 5 is effective and efficient in converting a broad range of aryl alcohols into the corresponding triflates, we next examined its recyclability. Thus, we recovered the polymer (a mixture of 5 and 8) at the end of the reactions and treated it with Tf₂O and Et₃N. As can be seen in Table 3, the same sample of 5 can be reused at least 3 times for the conversion of 6h to 7h, with only modest decrease in efficiency. Considering the small scale of the reactions performed, we consider the reported yields to be approximately equivalent. However, the reactions of the later cycles were somewhat sluggish compared to the initial reaction and required slightly longer reaction times. Nevertheless, it is important to note that the reactions were efficient in all cases and only the desired product was observed.
Lastly, we examined the possibility of incorporating basic amine moieties into 5 so that the triflation reactions might be performed without the requirement for a base to be added and thereby possibly eliminate the need for the filtration through silica gel to obtain pure product. Thus bifunctional polymer 9, which contains not only triflimide moieties, but also basic trialkylamine groups was prepared by the inclusion of monomer 10 in a 3:2 ratio compared to 4, in the polymerization process (Scheme 2). The loading levels of both the amine and triflimide functional groups were determined by elemental analysis to be 1.3 and 0.8 mmol g⁻¹, respectively, based on nitrogen and sulfur content. To our knowledge only one other such bifunctional polymer has been reported in the literature and it contains both basic pyridine moieties and catalytic 4-dimethylaminopyridine groups and it was used in esterification reactions. Unfortunately when 9 was used to convert 6h to 7h, only trace amounts (< 5%) of the desired product were observed by GC analysis, even after extended reaction times at elevated temperature.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Yield (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>88</td>
</tr>
<tr>
<td>3</td>
<td>95</td>
</tr>
<tr>
<td>4</td>
<td>92</td>
</tr>
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Table 3. Recycling of 5.

Scheme 2. Synthesis of bifunctional polymers 9 and 11. Reagents and conditions: (a) PhCl, AIBN, water, acacia gum, NaCl, 85 °C. (b) PhMe, AIBN, 85 °C.

In order to gain insight into the failure of 9 to be an efficient triflating reagent, we prepared the soluble, non-cross-linked polystyrene (NCPS) reagent 11 by co-polymerization of 4, 10, and styrene (Scheme 2), since it would be easier to characterize spectroscopically and be a homogeneous reagent. Analysis of 11 by IR, and ¹H and ¹⁹F NMR spectroscopy and comparison of this data with that of 4 indicated that the amine and triflimide groups are compatible with one another in the polystyrene matrix. Even when both 9 and 11 were subjected to the aqueous suspension polymerization reaction conditions, only minor signals indicating N-H bonds were observed in the IR spectra. Thus premature cleavage of the triflimide groups was probably not responsible for the poor results with 9. Reaction of 6h with 11 also only afforded low yield of 7h (ca 8%), indicating that the heterogeneous nature of 9 was also not responsible for its inefficiency. Thus, some unknown interaction between the amine and triflimide functional groups must responsible for the failure of the bifunctional polymers 9 and 11 to be useful triflating reagents.

3. Conclusions

We have prepared the new, insoluble polystyrene-supported triflimide reagent 5 and demonstrated its usefulness in the synthesis of a range of aryl triflates, including ones that contain aliphatic hydroxyl groups. This reagent is recyclable at least 3 times with no significant decrease in its efficiency. Finally, we report the synthesis of bifunctional polymeric reagents 9 and 11. Unfortunately these are not as efficient as 5 is in the preparation of aryl triflates, which may be due to micro-environmental factors that arise from bringing the amine and triflimide moieties together in the same polymer matrix.

Finally, we have attempted to use 5 in the synthesis of enol triflates from ketones, and in sample reactions the products formed required chromatographic purification, as is the case when 1 and 2 are used. Thus, considering the heterogeneity of 5 and the prolonged reaction times required compared to homogeneous small molecule reagents, we found no advantages to using 5 in enol triflate synthesis and therefore limited our study to the preparation of aryl triflates. Significantly, when 5 is used in such applications, the work-up and isolation of the aryl triflate product is simple, amenable to being performed in parallel in an automated fashion and can be completed in a matter of minutes. Thus it should be a useful tool in parallel synthesis, where the ability to simply isolate products with high purity is essential.

4. Experimental

4.1. General

All reagents were obtained from the Aldrich, Lancaster or Acros chemical companies and were used without further purification. All moisture sensitive reactions were carried out in dried glassware under a N₂ atmosphere. Tetrahydrofuran was distilled under a N₂ atmosphere over sodium and benzophenone. Dichloromethane was distilled under a N₂ atmosphere over calcium hydride. Merck silica gel 60 (230-400 mesh) was used for chromatography.
layer chromatography analysis was performed using glass plates coated with silica gel 60 F254. Gas chromatographic analyses were performed using an RTX-5 column with a Thermo Finnigan Focus chromatograph. NMR spectra were recorded using either a Bruker DRX 300 or an AV400 spectrometer. Chemical shift data is expressed in ppm with reference to TMS. HR EI-MS data was recorded on a Finnigan MAT 96 mass spectrometer.

4.1.1. N-(4-vinylphenyl)trifluoromethanesulphonimide (4). To a solution of 4-aminostyrene (5.40 g, 45.2 mmol) and Et3N (18.8 mL, 135.5 mmol) in anhydrous CH2Cl2 (100 mL) at -78 °C was added triflic anhydride (15.2 mL, 93.0 mmol). The reaction mixture was stirred at this temperature for 1 h and then warmed to rt and stirred for 1 h more. At this time, the reaction mixture was diluted with CH2Cl2 (400 mL) and then washed sequentially with saturated aqueous NaHCO3 (150 mL) and brine (150 mL). The organic phase was dried over MgSO4, filtered and concentrated in vacuo. The crude product was purified by silica gel chromatography (5% EtOAc/hexanes) to afford 4 as a white solid (15.58 g, 90%). 1H-NMR (300 MHz, CDCl3) δ 5.43 (d, 1H, J = 10.9 Hz), 5.85 (d, 1H, J = 17.6 Hz), 6.73 (dd, 1H, J = 17.6, 10.9 Hz), 7.35 (d, 2H, J = 8.5 Hz), 7.51 (d, 2H, J = 8.6 Hz). 13C-NMR (75 MHz, CDCl3) δ 113.3, 113.3-123.3 ( CCF = 323.2 Hz), 127.9, 131.1, 131.5, 135.3, 141.8. 19F-NMR (376 MHz, CDCl3) δ -71.1. IR (KBr, cm-1): 3073, 1633, 1510, 1145, 761, 700. Elemental analysis was used to determine the nitrogen content (2.9%) and the sulfur content (5.0%), and thus the loading levels of the amine and triflimide groups in 9 were 1.3, and 0.8 mmol g−1, respectively.

4.1.2. Janda/Jel®-NTf2 (5). A solution of acacia gum (6.0 g) and NaCl (3.8 g) in warm deionized water (45 °C, 150 mL) was placed in a 150 mL flanged reaction vessel equipped with a mechanical stirrer and deoxygenated by purging with N2 for 2 h. A solution of 4 (5.74 g, 15.0 mmol), styrene (4.26 g, 41.0 mmol), 1,4-bis(4-vinylphenoxy)butane 22d (0.34 g, 1.1 mmol), and AIBN (42.0 g, 1.3 mmol) in chlorobenzene (10 mL) was injected into the rapidly stirred aqueous solution. The resulting suspension was heated at 85 °C for 20 h. This mixture was washed with hot water (3 x 100 mL) and then placed in a Soxhlet extractor and washed with THF for 24 h. The beads were then washed sequentially with dichloromethane (250 mL), and then dried in vacuo for 24 h to afford 9 (5.4 g, 54%). IR (KBr, cm−1): 3498, 3027, 1606, 1510, 1145, 761, 700. Elemental analysis was used to determine the nitrogen content (2.9%) and the sulfur content (5.0%), and thus the levels of the amine and triflimide groups in 9 were 1.3, and 0.8 mmol g−1, respectively.

4.1.4. NCPS-(CH2NEt2)2NTf2 (11). To a solution of styrene (1.67 g, 16.0 mmol), diethyl(4-vinylbenzyl)amine (1.42 g, 7.5 mmol) and 4 (1.79 g, 5.0 mmol) in toluene (20 mL) was added AIBN (0.024 g, 0.14 mmol). The mixture was purged with N2 for 30 min and the solution was stirred at 85 °C for 24 h. The solution was concentrated in vacuo and the residue was taken up in 2 mL of THF. This solution was added dropwise to a vigorously stirred cold Et2O (0 °C, 200 mL). The white precipitate was filtered and dried to afford 11 as a white powder (1.6 g, 32%). 1H-NMR (400 MHz, CDCl3) δ 1.02-1.60 (br, 10H, 1H, 1.63-2.41 (br, 36H), 2.82-3.32 (br, 4H), 3.81-4.38 (br, 1H), 6.12-7.75 (br, 20H). 19F-NMR (376 MHz, CDCl3) δ -71.1. IR (KBr, cm−1): 3504, 3028, 1603, 1506, 1129, 762, 702.

4.2. General procedure for aryl triflate synthesis using 5.

Reagent 5 (0.47 g, 0.75 mmol) and Et3N (0.1 mL, 0.75 mmol) were added to a solution of 6 (0.375 mmol) in anhydrous CH2Cl2 (5 mL). The reaction mixture was shaken at rt until TLC analysis indicated the complete disappearance of 6 (4-16 h). At this time, the resin was filtered off and the filtrate was concentrated in vacuo. The resulting residue was then filtered through a plug of silica gel using CH2Cl2. Removal of the solvent afforded 7 that was determined to be essentially pure by 1H NMR.

The syntheses of 7b-I were performed at 50 °C and required 4, 5, and 2 d, respectively, for the complete disappearance of starting material. These products were purified by silica gel chromatography.

4.2.1. Characterization data for 7a:37 Colorless oil. 1H-NMR (300 MHz, CDCl3) δ 7.25-7.29 (m, 2H), 7.34-7.49 (m, 3H). 13C-NMR (75 MHz, CDCl3) δ 128.8-125.6 ( JCF = 318.7 Hz), 121.7, 128.8, 130.7, 150.1. 19F-NMR (376 MHz, CDCl3) δ -72.9. HR EI-MS: calculated for C9H13NO3F3, 225.9911; found 225.9913.

4.2.2. Characterization data for 7b:7 Colorless oil. 1H-NMR (300 MHz, CDCl3) δ 3.82 (s, 3H), 6.80 (t, 1H, J = 2.3 Hz), 6.85-6.94 (m, 2H), 7.33 (t, 1H, J = 8.3 Hz). 13C-NMR (100 MHz, CDCl3) δ 55.7, 107.5, 113.3, 114.2, 114.0-123.5 ( JCF = 319.0 Hz), 130.6, 150.3, 160.9. 19F-NMR
4.2.3. Characterization data for 7c:

White solid (mp 112.7-125.4) (JCF = 318.9 Hz), 122.4, 123.4, 133.8, 148.9. 19F-NMR (376 MHz, CDCl3) δ -72.9. HR EI-MS: calecd for C10H7SO4F3, 270.9527; found 270.9526.

4.2.4. Characterization data for 7d:

Colorless oil. 1H-NMR (300 MHz, CDCl3) δ 2.63 (s, 3H), 7.39 (d, 2H, J = 8.8 Hz), 8.07 (d, 2H, J = 8.9 Hz). 13C-NMR (75 MHz, CDCl3) δ 112.7-125.4 (JCF = 318.9 Hz), 122.0, 126.4, 147.5, 153.5. 19F-NMR (376 MHz, CDCl3) δ -73.0. HR EI-MS: calecd for C3H5NSF3O5, 270.9762; found 270.9760.

4.2.5. Characterization data for 7e:

Yellow solid (mp 52-56 °C). 1H-NMR (300 MHz, CDCl3) δ 7.49 (d, 2H, J = 8.9 Hz), 8.37 (d, 2H, J = 8.9 Hz). 13C-NMR (75 MHz, CDCl3) δ 117.5-123.9 (JCF = 318.9 Hz), 122.4, 123.4, 133.8, 148.9. 19F-NMR (376 MHz, CDCl3) δ -72.8. HR-EI-MS: calecd for C3H5BrF3O5, 303.9017; found 303.9016.

4.2.6. Characterization data for 7f:

White solid (mp 321-325 °C). 1H-NMR (300 MHz, CDCl3) δ 8.17 (d, 2H, J = 8.9 Hz), 8.45 (d, 2H, J = 8.9 Hz). 13C-NMR (75 MHz, CDCl3) δ 117.5-123.9 (JCF = 318.9 Hz), 122.4, 123.4, 133.8, 148.9. 19F-NMR (376 MHz, CDCl3) δ -73.0. HR EI-MS: calecd for C6H5ClO3F, 284.0330; found 284.0330.

4.2.7. Characterization data for 7g:

Yellow solid (mp 52-56 °C). 1H-NMR (300 MHz, CDCl3) δ 7.49 (d, 2H, J = 8.9 Hz), 8.37 (d, 2H, J = 8.9 Hz). 13C-NMR (75 MHz, CDCl3) δ 112.7-125.4 (JCF = 318.9 Hz), 122.9, 126.4, 147.5, 153.5. 19F-NMR (376 MHz, CDCl3) δ -73.0. HR EI-MS: calecd for C6H5ClO3F, 284.0330; found 284.0330.

4.2.8. Characterization data for 7h:

Yellow solid (mp 52-56 °C). 1H-NMR (300 MHz, CDCl3) δ 7.49 (d, 2H, J = 8.9 Hz), 8.37 (d, 2H, J = 8.9 Hz). 13C-NMR (75 MHz, CDCl3) δ 112.7-125.4 (JCF = 318.9 Hz), 122.9, 126.4, 147.5, 153.5. 19F-NMR (376 MHz, CDCl3) δ -73.0. HR EI-MS: calecd for CH3SO4F3, 256.0017; found 256.0016.

4.4.2.10. Characterization data for 7j:

Yellow oil. 1H-NMR (300 MHz, CDCl3) δ 2.62 (s, 3H), 3.98 (s, 3H), 7.32 (d, 1H, J = 8.4 Hz), 7.57 (d, 1H, J = 8.4, 2.0 Hz), 7.65 (d, 1H, J = 1.9 Hz). 13C-NMR (100 MHz, CDCl3) δ 26.5, 56.4, 112.3, 114.0-123.5 (JCF = 318.5 Hz), 122.6, 122.5, 137.8, 141.9, 151.7, 196.3. 19F-NMR (376 MHz, CDCl3) δ -72.8. HR EI-MS: calecd for C4H5ClO3F, 298.0123; found 298.0116.

4.4.2.11. Characterization data for 7k:

Yello oil. 1H-NMR (300 MHz, CDCl3) δ 1.49 (d, 3H, J = 6.5 Hz), 2.07 (br, 1H), 4.93 (q, 1H, J = 6.5 Hz), 7.24 (dd, 2H, J = 6.8, 2.0 Hz), 7.45 (dd, 2H, J = 6.8, 1.7 Hz). 13C-NMR (100 MHz, CDCl3) δ 25.3, 69.4, 114.0-123.5 (JCF = 318.8 Hz), 121.3, 127.2, 146.3, 148.6. 19F-NMR (376 MHz, CDCl3) δ -73.0. HR EI-MS: calecd for C6H7ClO3F, 270.0174; found 270.0168.

For structural proof, 7j was oxidized to the corresponding aldehyde using PDC (2.5 equiv) in CH2Cl2 at rt for 2 h (83% yield). Characterization data for this aldehyde: 1H-NMR (300 MHz, CDCl3) δ 7.47 (d, 2H, J = 8.6 Hz), 8.01 (d 2H, J = 8.6 Hz), 10.05 (s, 1H). 13C-NMR (125 MHz, CDCl3) δ 114.9-122.5 (JCF = 318.9 Hz), 122.3, 131.8, 136.0, 153.2, 190.1. 19F-NMR (376 MHz, CDCl3) δ -72.7. HR EI-MS: calecd for C4H5SO4F3, 253.9861; found 253.9860.

For structural proof, 7k was oxidized to 7h using PDC (2.5 equiv) in CH2Cl2 at rt for 3 h (87% yield). Characterization data for this product agreed with that which was previously observed.

4.2.12. Characterization data for 7l:

White solid (mp 32-35 °C). 1H-NMR (400 MHz, CDCl3) δ 1.57 (s, 6H), 7.22 (d, 2H, J = 8.9 Hz), 7.56 (d, 2H, J = 8.9 Hz). 13C-NMR (75 MHz, CDCl3) δ 32.1, 72.6, 112.8-123.5 (JCF = 318.7 Hz), 121.3, 126.9, 148.6, 150.0. 19F-NMR (376 MHz, CDCl3) δ -72.9. HR EI-MS: calecd for C3H11POP3, 284.0330; found 284.0363.

4.3. Procedure for regeneration and reuse of polymer 5.

The polymeric reagent recovered from the aryl triflate synthesis reactions (a mixture of 5 and 8) was treated with triflic anhydride (3 equiv) and Et3N (3 equiv) in anhydrous CH2Cl2 at -78 °C for 1 h and then warmed to room temperature and stirred for 18 h more. The polymer 5 was filtered and washed as before.

The same sample of 5 was used 4 times to prepare 7h. For each tritation cycle, the reaction was monitored by TLC analysis and the product was purified and characterized as before.

4.4. Use of polymers 9 and 11 for aryl triflate synthesis.

Reagent 9 (2 equiv of –NTf2, 3 equiv of –CH2NEt2) was used in CH3Cl2, DMF, 1,4-dioxane at rt (70 °C for the later two solvents) for the conversion of 6h to 7h. Samples of the reaction solutions were intermittently analyzed by gas chromatography to determine the extent of reaction. After up to 5 d, 7h was formed in less than 5% yield under all reaction conditions.

Reagent 11 (2 equiv of –NTf2, 3 equiv of –CH2NEt2) was used in CH3Cl2 at rt. After 3 d, analysis by gas
chromatography indicated that 7h was formed in only 8% yield.

Acknowledgments

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