

## Synthesis and regeneration of reactive polymers bearing triphenylphosphine dichloride functional groups using triphosgene

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### Summary

A new methodology is described for the synthesis of reactive polymers bearing triphenylphosphine dichloride groups by the use of triphosgene. These materials show high reactivity for the room temperature conversion of benzyl alcohol to benzyl chloride. In one hour, yields higher than 90% were achieved using reactive copolymers with up to 25 w% divinylbenzene (DVB). The functional groups can be easily and efficiently regenerated using 1.0 mol of triphosgene for every 2.6 moles of phosphine in the polymer. Preliminary results showed up to 40% conversion of benzyl alcohol in column reactions using regenerated polymers at 5 to 10 min contact times.

### Introduction

In the last decade, rapid progress has been made in the development of reactive polymers (1-4). A polymeric reagent is a polymer with reactive functional groups available for chemical transformations of an added substrate. Some of the advantages of using a polymeric reagent rather than a non-macromolecular one are:

- a). Product isolation is simplified, since the polymers are either insoluble or easily precipitated (5).
- b). Some secondary reaction products are fixed in the polymer; this makes purification of the main product easy (6).
- c). The microenvironment within the polymer can be advantageous for some applications (5).
- d). The functional groups in the polymer are regenerable and therefore the polymeric reagent is potentially re-usable (3).
- e). If a reaction proceeds very readily, it can be carried out by preparing a column of the reactive polymer and then passing the other reactants through the column (3).

A desired functional group can be introduced into a polymer by one of the following two methods or a combination of both:

- a) The polymerization or copolymerization of appropriately substituted monomers.
- b) The chemical modification of a suitable preformed polymer.

As pointed out by Akelah (4) each of the two approaches has advantages and disadvantages. But when a high degree of functionalization is desired, for example, to reduce the amount of polymer required for some reaction or in order to achieve an appropriate material for column-reactions, the polymerization of substituted monomers is the method of choice.

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Polymeric materials with phosphine functional groups have a wide field of applications. These include their use as chelating agents, as catalysts and as reagents for organic synthesis (4). One of the more interesting phosphine functional groups is triphenylphosphine dichloride, since it is a key reagent for the synthesis of alkyl chlorides from alcohols, acyl chlorides from organic acids, nitriles from primary amides and geminal dichlorides from aldehydes and ketones (7). Reactive polymeric systems involving triphenylphosphine dichloride as an intermediate, like polymer-supported triphenylphosphine/ $\text{CCl}_4$  and polymer-supported triphenylphosphine/hexachloroethane, were used for the same kind of reactions (8-10) and also for peptide synthesis (11,12). Direct synthesis of polymer-supported triphenylphosphine dichloride was first reported by Relles and Schluenz (13) who used a four-step chemical modification of polystyrene-beads. The last step involves the reaction of polymer-supported triphenylphosphine with excess phosgene. The same reaction with phosgene was used for the regeneration of the functional groups in the polymer after use. Appel and Willms (12) also used excess phosgene for the reactivation of polymer-supported triphenylphosphine/hexachloroethane. Here we want to report the use of bis(trichloromethyl)carbonate, "triphosgene", a solid, in stoichiometric quantities for the synthesis and regeneration of triphenylphosphine dichloride in reactive polymers, obtained by the polymerization of appropriate monomers to achieve high functionalized polymeric reagents suitable for use in column reactions.

## Experimental

### *Synthesis of triphenylphosphine-functionalized polymers*

The functionalized monomer p-styryldiphenylphosphine was obtained through a Grignard-reaction starting from 4-chlorostyrene and chlorodiphenylphosphine by the method described in (14).

Free radical homopolymerizations were carried out in Schlenk tubes in toluene solution with 0.7 mol% to 1.4 mol% azobisisobutyronitrile (AIBN) as initiator. The mixtures were degassed at least three times at  $-40\text{ }^\circ\text{C}$  and then filled with oxygen-free argon prior to sealing. The polymerizations were carried out at  $60\text{ }^\circ\text{C}$  for 48 h. The Schlenk tube was opened and its contents added to a large excess of hexane, to precipitate the polymers. The polymers were filtered and dried overnight at  $30\text{ }^\circ\text{C}/0.1\text{ mmHg}$ . Functionalized crosslinked polymers were obtained by copolymerization of p-styryldiphenylphosphine with different amounts of divinylbenzene (DVB) using 1 mol% of AIBN. Since DVB (Aldrich) is a mixture of 55% DVB and 45% of ethylvinylbenzene-isomers, the synthesized crosslinked polymers with weight percentages of pure DVB from 4% to 35% have also different amounts of ethylvinylbenzene as a comonomer. The DVB-reagent was passed through a t-butyl-catechol-remover column (Aldrich) prior to its addition to the copolymerization mixtures. The copolymerizations were performed with the same methodology described above with one exception: after copolymerization the crosslinked polymers were filtered from toluene and washed several times with fresh toluene, prior to the addition of hexane, in order to eliminate non-crosslinked material.

Molecular weights of homopolymers were determined with Ubbelohde-viscosimeters in toluene at  $25\text{ }^\circ\text{C}$  in a Koehler viscosity bath. The swelling degree of the crosslinked polymers was determined in methylene chloride by weight difference of dry and swollen samples assuming  $1.0\text{ g/cm}^3$  density for all polymeric materials. The thermal properties were measured by a simultaneous DTA-TG method (STA-780, Stanton-Redcroft) in dry-nitrogen flux. A heating rate of  $10\text{ K/min}$  and calcinated alumina as reference material were used.

### *Triphenylphosphine dichloride functionalized polymers*

These polymers were obtained by modification of the already synthesized polymers (homopolymers and crosslinked polymers) with triphenylphosphine. Under dry nitrogen flux 50 mL of dry methylene chloride was added to approx. 1.0 g of the polymers and stirred for one hour to allow complete dissolution/swelling of the materials. A concentrated solution of triphosgene in dry methylene chloride was added dropwise. According to previous work (15) 1.0 mol triphosgene was used for every 2.6 moles of triphenylphosphine in the polymer. The mixture was stirred at room temperature for 2 h and the solvent was removed under reduced pressure.

### *Conversion of benzyl alcohol to benzyl chloride*

Since triphenylphosphine dichloride is humidity sensitive, the functionalized polymers with the phosphinedichloride group were used immediately after preparation in a reaction with benzyl alcohol. For this reaction, 50 mL of dry methylene chloride was added to the reactive polymers under nitrogen flux and stirred for 1 h to allow complete dissolution/swelling. Then benzyl alcohol, 1.0 mol for every 1.7 moles of phosphine in the polymer, was added dropwise. The reaction was conducted at room temperature for 1 h, the solvent was removed under reduced pressure, and the products were extracted 2 times with 20 mL each of cold pentane, the total volume being reduced to 5 mL and then analyzed. For the initial reaction with each synthesized polymer 1  $\mu$ L of the pentane solution of products was analyzed by gas chromatography-mass spectrometry (GC-MS, Hewlett-Packard 5890II/5971). Subsequent reactions were analyzed by gas chromatography with flame ionization detector (GC-FID, Hewlett-Packard 5890II) using the same capillary column (HP-5) in both instruments. The products were identified by MS spectra.

### *Regeneration of the reactive polymers*

After using the reactive polymers for the above reaction with benzyl alcohol, the polymers' functional groups are now triphenylphosphine oxides. Since it has been reported that phosgene readily converts triphenylphosphine oxide into triphenylphosphine dichloride (13), we used an analogous reaction for the spent polymers, using triphosgene for the same purpose. Under dry nitrogen flux 50 mL of dry methylene chloride was added to approx. 1.0 g of the spent polymer and stirred for one hour to allow complete dissolution/swelling of the materials. A concentrated solution of triphosgene in dry methylene chloride was added dropwise, using 1.0 mol triphosgene for every 2.6 moles of triphenylphosphine oxide in the polymer. The mixture was stirred at room temperature for 2 h and then the solvent removed under reduced pressure.

### *Column-reactions*

A glass column (90 mm length, 6 mm I.D.) was plugged with glass-wool and packed with freshly regenerated reactive polymer. Dry pentane was added and the polymer allowed to swell. The calculated amount of benzyl alcohol, 1.0 mol for every 1.7 moles of phosphine in the polymer, was added to the column and then eluted with 10 mL of pentane under hand-pressure using a rubber bulb. The total contact time between the alcohol and the reactive polymer was 5-10 min. The eluate was filtered with 0.2 $\mu$  syringe filters and then 5 $\mu$ L from this solution was analyzed on GC-FID.

Table 1: Physical properties of the functionalized polymers

Parameter	0	4	8	15	25	35
	weight % DVB	weight% DVB	weight% DVB	weight% DVB	weight% DVB	weight% DVB
Q	-	13.7	8.5	7.5	6.9	6.4
T <sub>g</sub>	203	94	100	126	131	148
T <sub>10</sub>	379	388	385	162*	176*	329
T <sub>D</sub>	445	411	433	436	446	454

\* Due to the presence of volatiles

## Results and Discussion

### *Synthesis and characterization of the reactive polymers*

The substituted monomer p-styryldiphenylphosphine was obtained in 50% yield in pure form according to <sup>1</sup>H-NMR and IR spectra. By solution homopolymerization of p-styryldiphenylphosphine, linear polymers with triphenylphosphine groups in every repeat unit were obtained, yielding high functionalized reactive polymers. The measured intrinsic viscosities [η] were between 0.12 and 0.16 dL/g. For comparison, Rabinowitz et. al (16) reported [η] from 0.14 to 0.28 dL/g for the same polymer. The highest molecular weight obtained was 61 000 g/mol, calculated using reported Kuhn-Mark-Howink-constants for poly(4-chlorostyrene) (17) and the molecular mass of our monomer-unit.

The thermal properties for this polymer and all the DVB-crosslinked copolymers are reported in Table 1. The glass-transition temperatures (T<sub>g</sub>) for the polymers appears higher than that of polystyrene [T<sub>g</sub> = 80 °C to 100 °C, according to (17)], the homopolymer showing the highest value. The DVB-crosslinked copolymers showed an increase of T<sub>g</sub> with higher content of crosslinking-agent, due to the lower mobility of the chains in higher cross-linked species. The increase in T<sub>g</sub> is comparable to the reported increase for polystyrene-DVB copolymers, showing an increase from 102 °C to 133 °C from gels with 5 weight% DVB to gels with 20 weight% of DVB (3). Swelling (Q) of the copolymers confirm the T<sub>g</sub> behaviour. The lower the DVB content in the copolymers, the higher the swelling degree (see Table 1, first row).

The thermal stability of the homopolymer is also higher than that for polystyrene which shows 10% weight loss at T<sub>10</sub> = 343 °C (17), but is lower than that reported in (16) for poly[4(diphenylfosfinyl)styrene], the same homopolymer (T<sub>10</sub>= 425 °C). Finally, the mean temperature for the first decomposition event T<sub>D</sub> shows an increasing tendency for the higher crosslinked polymers. The homopolymer again has a high value.

Evidence for the generation of triphenylphosphine dichloride groups in the polymers after treatment with triphosgene was obtained by comparison of the IR spectra of the resulting polymers with the original product (Aldrich) triphenylphosphine dichloride. Finally the efficiency of this functionalization method was tested through the conversion of benzyl alcohol to benzyl chloride using the generated reactive polymers.

Table 2: Results of conversion of benzyl alcohol using reactive polymers at room temperature.

Type of Polymer	Benzyl chloride yield% original polymer	Benzyl chloride yield % regenerated polymer	Benzyl chloride yield% column reaction
0 weight% DVB	40	75	35
4 weight% DVB	100	49	-
8 weight% DVB	100	100	41
15 weight% DVB	94	94	-
25 weight% DVB	89	94	39
35 weight% DVB	84	73	37

#### *Conversion of benzyl alcohol to benzyl chloride*

Table 2 shows the percent yield of benzyl chloride as a result of the conversion of benzyl alcohol using the reactive polymers. In the literature, the preparation of alkyl chlorides from alcohols using reactive polymers is focused on polymer-supported triphenylphosphine/ $\text{CCl}_4$ . For example Harrison, Hodge et al. (9) reported the conversion of different alcohols to alkyl chlorides using this system, with yields from 40% to 100% at 78 °C after one to six hours. After 4 h at 40 °C, they obtained 62% conversion of benzyl alcohol to the corresponding chloride with 1% DVB crosslinked polymers and only 26% with the linear polymers. At 78 °C (reflux) they achieved the highest value (91% yield) using the linear polymer for 2 h. Sherrington et al. (8) obtained 45 % benzyl chloride after 9 h at 78 °C for high crosslinked (37% DVB) triphenylphosphine-polymer/ $\text{CCl}_4$ . We found only one report for triphenylphosphine dichloride-polymer (2% crosslinked) in which Relles and Schluenz (13) obtained 88% yield in the chlorination of benzyl alcohol, but the temperature and time were not reported.

Our results, showing yields of up to 100% (first row, Table 2) for the chlorination of benzyl alcohol in reactions carried out at room temperature for 1 h, are interesting in two ways. First, the mild reaction conditions compare favorably with literature reports. Second, the yields up of up to 90% with DVB contents of 25% and lower are encouraging since it is believed that high yields can only be achieved with low crosslinked polymers, commonly 1-2 % DVB. Higher DVB content can lead to diffusion control. Although in (8) 100% yield is reported for conversion of 1-octanol to 1-chlorooctane at 78 °C after 9 hour using 15% DVB crosslinked polymers, the increase to 25% DVB lowered the yield to 50%, and for 37% DVB no product was formed. Our results with the crosslinked polymers also show a decrease in the yield of benzyl chloride with increasing crosslink-density, but not as dramatic. It lowered the yield from 100% (8% DVB polymer) to 84% (35% DVB polymer).

With these results we contribute in finding a solution to two of the major drawbacks for the application of reactive polymers in column reactions, namely, the high reaction temperatures (reflux) and the low crosslink-density leading to very soft materials. These drawbacks make column reactions unsuitable.

#### *Regeneration and column reactions*

An important feature in the application of reactive polymers in column reactions is the regeneration of the active functional groups after use; in our work those active groups are transformed to triphenylphosphine oxides. Two methods are described in the literature for

the regeneration of these groups: direct conversion by phosgene back to the phosphine dichlorides (13) and reduction of triphenylphosphine oxides to triphenylphosphine using trichlorosilane (9,18-20).

Using the reduction to triphenylphosphine with trichlorosilane literature reports show: in (9) a dramatic loss of chlorination capacity of 63% after regeneration; in (2) a decrease in the yield of products from 67% originally obtained to 44% yield after the first and to 20% yield after the second regeneration; and in (18) 10% loss of triphenylphosphine functional groups after two regenerations.

In the direct conversion with excess phosgene to triphenylphosphine dichloride (13) ready regeneration is reported but not directly quantified. Our chlorination results (second column of Table 2) with the regenerated polymers by the triphosgene method (2 h, room temperature in stoichiometric amounts) show that for most of the polymers (4 of 6), no decrease in the activity was found. In some reactions with lower yields of benzyl chloride, benzyl chloroformate byproduct was found. This product was the main product in the reaction from benzyl alcohol with triphosgene; in an experiment under conditions similar to the chlorination reported here but using only triphosgene and no polymer, after 2 h, GC analysis of the reaction mixture showed 60% of unreacted starting materials, 34% of benzyl chloroformate, and only 6% of benzyl chloride. Care should be taken to eliminate residual triphosgene in the triphenylphosphine dichloride functionalized polymers, in order to improve the yields of benzyl chloride.

Using triphosgene, we have a method for generation and regeneration of triphenylphosphine dichloride functionalized polymers, capable of producing alkyl chlorides from alcohols with consumption of triphosgene in exact, measurable amounts (see Figure 1). The last column of Table 2, shows preliminary result of the application of the regenerated reactive polymers to column reactions. As a result of single elution of

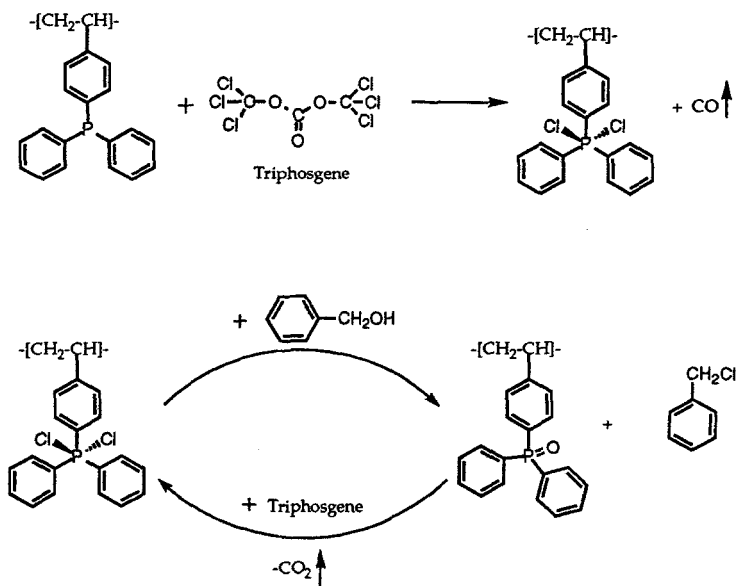


Figure 1: Synthesis and regeneration of the reactive polymers with triphenylphosphine dichloride functional groups using triphosgene.

benzyl alcohol with contact times with the polymers of 5 to 10 min at room temperature, ca. 40% yield of benzyl chloride was obtained. These results are very encouraging for the potential application of these reactive polymeric materials for column reactions.

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