methyl acetyl phosphate. D-3-Hydroxybutyrate dehydrogenase is subject to very rapid ($t_{1/2}$ ~2 min) specific inactivation. We shall report detailed results on this matter elsewhere.

# Synthesis and Reactivity of Polymer-Supported Reducing Agents with Chemically Modified Surfaces

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Insoluble polymeric reagents have been developed which oxidize,[1] acylate,[2] epoxidize,[3] halogenate,[4] and hydrogenate[5] to name a few. Their usefulness arises from the simple reaction workup[6] (filtration of the polymer and removal of solvent) and from the ability to recycle spent polymer.[7] Several hydride-delivering polymers are known. One of them, bearing organotin dihydride groups,[8] requires a five-step synthesis and reacts but slowly (24–25 h) with carbonyl compounds. The others are anion-exchange resins having borohydride[9] or cyanoborohydride[10] counterions and a poly(4-vinylpyridine–borane)[11] which gives only low yields of carbonyl reduction in refluxing benzene. We have synthesized solid BH_3 derivatives of poly(2-vinylpyridine) and poly(4-vinylpyridine) which reduce carbonyl groups in high yield at room temperature. In addition, we have studied how partial alkylation of the pyridine nitrogens with ethyl bromide or dodecyl bromide benefits the reducing properties of the polymeric reagents.

A polymer-supported reducing agent was prepared by treating poly(2-vinylpyridine) with borane–methyl sulfide complex in THF (eq 1). The product precipitates from
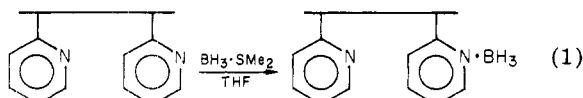
solution. Thus, "reducing beads" can be obtained in a single step starting with commercially available materials. When this polymer was mixed with 6 N HCl (to eventually give a homogeneous solution), the resulting hydrogen evolution corresponded to 77% complexation of the pyridine rings. Not all of this borane is available for reducing carbonyls, however. A heterogeneous reduction of excess octanal in benzene by solid polymer showed that 32% of

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Table I. Heterogeneous Reductions of Aldehydes and Ketones in Benzene at Room Temperature by Solid Poly(2-vinylpyridine)–BH_3 Complex

reactant	reaction time, h	product	yield,^{a} %
	3		100^b
	3		94
	3		93^c
	3		0^d
n-$C_7H_{15}CHO$	1	n-$C_7H_{15}CH_2OH$	98 (87^e)
C_6H_5CHO	3	$C_6H_5CH_2OH$	65^e
$C_6H_5CH_2CHO$	24	$C_6H_5CH_2CH_2OH$	100
$C_6H_5CH{=}CHCHO$	1	$C_6H_5CH{=}CHCH_2OH$	65
$C_6H_5COOH^f$	20	$C_6H_5CH_2OH$	11
$C_6H_5COOCH_3$	20	$C_6H_5CH_2OH$	13
C_6H_5COCl	44	$C_6H_5CH_2OH$	44
$C_6H_5COCH_3$	3	$C_6H_5CH(OH)CH_3$	82

^{a} Except for two runs, yields were measured by GLC using either 1-phenylhexane, 1-phenyloctane, diphenylmethane, or naphthalene as an internal standard. ^{b} 41% cis:59% trans. ^{c} 46% cis:54% trans. ^{d} Unreacted ketone was observed by GLC. ^{e} Isolated yield after distillation. ^{f} Converted into the methyl ester with CH_2N_2 before GLC analysis.

the boranes fail to react with the aldehyde; presumably, these boranes are buried beneath the polymer surface.

Monomeric pyridine–borane in refluxing benzene reduces aldehydes and ketones in moderate yield.[12] In contrast, our polymeric analogue reduces these carbonyl compounds in high yield at room temperature but only in the presence of $BF_3 \cdot OEt_2$ (Table I). The role of the additive is not clear; it may facilitate reduction by complexing with the carbonyl oxygen or it may displace borane from the polymer surface. The possibility that the carbonyl reductions are in fact not true surface reactions seems unlikely because polymer washed with hot benzene retains its full reducing capabilities.[13] Furthermore, swelling the polymer in refluxing benzene for 1 h prior to reduction at room temperature greatly facilitates the reaction. Thus, untreated polymer plus octanal gives 39% octanol after 1 h, whereas the yield increases to 98% if the polymer is first exposed to hot benzene. Stirring the polymeric reagent for 12 h in cold benzene likewise improves the reaction time.

In a typical run, 0.25 g of polymer was heated with 3 mL of refluxing benzene for 1 h. When the benzene had cooled, the following were added to the reaction flask: 1 mmol of carbonyl compound, 1 mmol of $BF_3 \cdot OEt_2$, an internal standard for GLC analyses and 2 mL of benzene. The reaction was allowed to proceed at room temperature after which 0.5 mL of saturated $NaHCO_3$ was added and the solids were removed by filtration. Either the filtrate was assayed by gas chromatography or the product was isolated from the solvent, purified, and weighed. As can be seen from Table I, the reductions proceed in high yield for aliphatic and aromatic aldehydes and ketones but not for acids, esters, acid chlorides, and α,β-unsaturated ke-

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(13) Pyridine–borane complex does not dissociate at 100 °C and 1.8 mm pressure. See A. B. Burg, *Rec. Chem. Prog.*, **15**, 159 (1954).

tones. The ability of the polymer to reduce 3-methyl-cyclohexanone but not 3-methyl-2-cyclohexen-1-one is an interesting and potentially useful feature.

Borane complexes of poly(4-vinylpyridine) and poly(4-vinylpyridine-*co*-styrene) react sluggishly with carbonyls. In an effort to alleviate this situation, we modified the surface of these polymers by partial alkylation. Thus, the poly(4-vinylpyridine) or its copolymer was treated with dodecyl bromide in 1:1 nitromethane/nitroethane at 65 °C for 24 h. The extent of alkylation was determined by elemental analysis and by NMR (i.e., by integrating the aromatic proton signals from quaternized and nonquaternized pyridine rings). Most polymer samples had 48 ± 5% of their residues derivatized. The polymer was then reacted with $BH_3 \cdot SMe_2$ in the usual manner such that 44 ± 5% of the total pyridines was associated with BH_3. It was found that the modified polymer reduced octanal under standard conditions (see Experimental Section) with an average yield of 86% in 5 min. Nonalkylated polymer gave only 66% yield in 8 h. Clearly, alkylation with dodecyl groups produces a remarkably effective polymeric reducing agent.

Two reasonable explanations exist for the efficient reduction by "laurylated" polymer: (1) The octanal substrate adsorbs more readily on polymer bearing long hydrophobic chains. (2) The additional positive charge on the polymer facilitates reduction. The validity of the second alternative is suggested by our finding that polymer which is 50% alkylated with ethyl groups reacts as rapidly as the "laurylated" material. Very likely, therefore, the enhanced positive charge on the polymer chain causes it to assume less compact configurations,[14] thereby exposing the reactive sites to external aldehyde. The *N*-alkylpyridinium ions could also promote the release of borane or stabilize the transition state for the reductive process.

In summary, we have developed a new polymer reducing agent which converts aldehydes and ketones into alcohols under mild conditions, with high yield and particularly easy workup. The potential of surface-modified polymers in selective reductions of only one group in a symmetrically bifunctional molecule (a feat not possible in the absence of adsorption) remains to be determined.

Experimental Section

Materials. Commercially available polymers were used exclusively; it was felt that a methodology requiring the synthesis of polymers would lack general utility. Thus, poly(2-vinylpyridine) was purchased from Aldrich and poly(4-vinylpyridine) from Polysciences. Aldrich poly(4-vinylpyridine-*co*-styrene) with a 10% styrene content seemed to have more favorable solubility characteristics than the poly(4-vinylpyridine) but behaved similarly in the alkylation experiments.

Procedure A. A solution of 10 g of poly(2-vinylpyridine) in 100 mL of purified THF was added dropwise to 50 mL of $BH_3 \cdot SMe_2$ in THF (2 M) cooled in an ice bath. The mixture was stirred for 20 h (which is believed to be longer than necessary; this point was not checked). Hexane (100 mL) was then added and the stirring continued for another 12 h. The resulting precipitate was removed by filtration, washed with hexane, and dried under reduced pressure for 24 h at 45 °C to give 11.3 g of polymer–borane complex. Polymer prepared by this procedure requires 1 h in refluxing benzene for optimal reducing power. Its shelf-life at room temperature is at least 4 weeks.

Procedure B. A solution of 5.0 g of poly(2-vinylpyridine) in 50 mL of dry THF was added dropwise to 25 mL of $BH_3 \cdot SMe_2$ in THF (2 M) cooled in an ice bath. The mixture was stirred for 1 h after which 50 mL of dry benzene was added and stirring continued for another 12 h. The suspension was filtered to collect the polymer which was then washed with dry benzene (3 × 50

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(14) G. A. Crosby and M. Kato, *J. Am. Chem. Soc.*, **99**, 278 (1977).

mL). After being dried for 5 h in vacuo at 40 °C, the polymer weighed 5.6 g. This material need not be pretreated with hot benzene.

The products from methods A and B are fine powders (mainly 60 mesh or smaller) that were used without grinding. If one adds the borane to the polymer (reversing the procedures described above), then the polymer forms an undesirable coagulate.

Reduction of Octanal. Polymer–borane complex from procedure A (0.25 g) was exposed to 3 mL of refluxing benzene for 1 h. The benzene was cooled, and 0.128 g (1 mmol) of octanal and 1 mmol of $BF_3 \cdot OEt_2$ were added (along with an internal standard in 2 mL of dry benzene). After 3 h at room temperature, the reaction mixture was shaken with saturated aqueous $NaHCO_3$ and filtered through Celite. Analysis of the filtrate by GLC showed that octanol was produced in 98% yield.

Reduction of Benzaldehyde. Dry benzene (25 mL) over 1.50 g of polymer–borane complex from procedure A was boiled under reflux for 1 h. The benzene was cooled, 1.28 g of benzaldehyde and 1.41 g of $BF_3 \cdot OEt_2$ in 5 mL of benzene were added, and the mixture was stirred for 1 h. Saturated aqueous $NaHCO_3$ (2 mL) was mixed with the benzene, the solids were removed by filtration, and the filtrate was washed with aqueous $NaHCO_3$ and 1 N HCl. After the benzene was removed, the product was distilled under reduced pressure to give 0.85 g (65%) of benzyl alcohol.

Polymer Alkylation. Poly(4-vinylpyridine-*co*-styrene) (2.22 g) was dissolved in 56 mL of 1:1 nitromethane/nitroethane and traces of insoluble material were removed by filtration. Redistilled dodecyl bromide (2.30 mL) was then added, and the solution was heated at 65 °C for 24 h. Alkylated polymer, isolated by precipitating the solid from small aliquots of the reaction mixture with 5 volumes of hexane, was subjected to elemental and NMR analyses. The remainder of the polymer solution was added slowly to 20 mL of borane–methyl sulfide complex in THF (2 M) cooled in an ice bath. After the solution was stirred for 1 h, 20 mL of benzene were added and the stirring was continued for another 48 h. The final polymeric product was precipitated with excess hexane, washed several times with hexane, and dried under reduced pressure at 50 °C for 24 h. The borane content was determined by volumetric measurement of H_2 in the presence of strong acid. Ethylated polymer was made in much the same manner.

Synthesis of 4-Deoxy-D-*lyxo*-hexose

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In connection with a program to investigate the effects of sugar analogues on glycoprotein biosynthesis, a convenient and efficient synthesis of 4-deoxy-D-*lyxo*-hexose (7) (4-deoxy-D-mannose) was required. This deoxy sugar was first prepared by Černý and co-workers via a multistep sequence that employed 1,6-anhydro-β-D-glucopyranose as starting material.[1] In this report a six-step synthesis of