Pyridine Rings as Protected 2° Amines: Facile Hydrogenation of Heterocyclic Aromatic Polymers

Yoko Aoyama[†] and Bruce M. Novak*[,‡]

Department of Polymer Science and Engineering, University of Massachusetts, Amherst, Massachusetts 01003, and Department of Chemistry, North Carolina State University, Raleigh, North Carolina 27695

Received June 11, 2001

Amines are one of the more versatile functional groups in organic chemistry as evidenced by their inherent ability to act as bases, acids, nucleophiles, reductants, ligands for transition metals, photoinduced electron-transfer agents, and protecting groups.[1] Furthermore, they are key participants in a plethora of biological processes.[2] These same useful attributes of the amine are carried over to their polymeric analogues, and as a result, polyamines are useful in applications ranging from paper sizing to pharmaceutical practices.[3] Unfortunately, this same portfolio of reactivities also makes their incorporation into polymers problematic. Hence, polymers bearing simple amines are not common and often difficult to prepare. Motivated by the above, we have been interested in developing synthetic methodologies that allow the facile incorporation of amines into polymers. Herein, we would like to report on the hydrogenation of homo- and copolymers possessing pyridine rings to form a family of secondary and tertiary amine polymers.[4] Used in this fashion, the pyridine moiety can be viewed as a "protecting group" for simple alkylamines.

We favor the pyridine moiety as a practical precursor for several reasons. First, both 2- and 4-vinylpyridine are versatile monomers themselves and are amenable to polymerization though a variety of techniques including anionic,[5] radical,[6] ATRP,[7] and, in some cases, coordination−insertion mechanisms.[8] Second, they are readily converted into secondary and tertiary amines through hydrogenation.[9] This conversion turns out to be nontrivial as evidenced by very large increases in basicity (e.g., pK_b = 8.8 and 2.8 for pyridine and piperidine, respectively)[10] and by the large changes in solubility (vide infra).

Carbon-based molecules have a strong thermodynamic preference toward saturation, and aromaticity should be viewed as, at best, a compromise. In accordance with this, the hydrogenation of unsaturated[11] and aromatic[12] polymers has been extensively reported, and it can be successfully performed on a commercial scale.[13] Like benzene, the hydrogenation of pyridine is exothermic. At the MP2 level, we calculate the heats of hydrogenation for toluene and 4-methylpyridine to be −41.2 and −31.6 kcal/mol, respectively. The enthalpy difference of about 10 kcal/mol is essentially equivalent to the differences in bond strengths between the C−H and N−H bonds, $\Delta\Delta H \approx BDE_{C-H} - BDE_{N-H}$.

Our first attempts at the hydrogenation of poly(4-vinylpyridine) (4-PVP) using known homogeneous catalysts[14] met with only limited success. Under various conditions of temperature, pressure, and concentration, the known hydrogenation catalysts $(PPh_3)_3RhH(CO)$ and $[(Py)_2(DMF)RhCl_2]^+[BH_4]^-$ were essentially ineffective, and $(PPh_3)_3RhCl$ gave maximum hydrogenation levels of approximately 50% (130 °C, 210 psi of H_2, 170 h). We feel that the high temperatures and long reaction times lead to catastrophic decomposition of the catalysts. There is certainly latitude for improvement here, and alternatives are being explored.

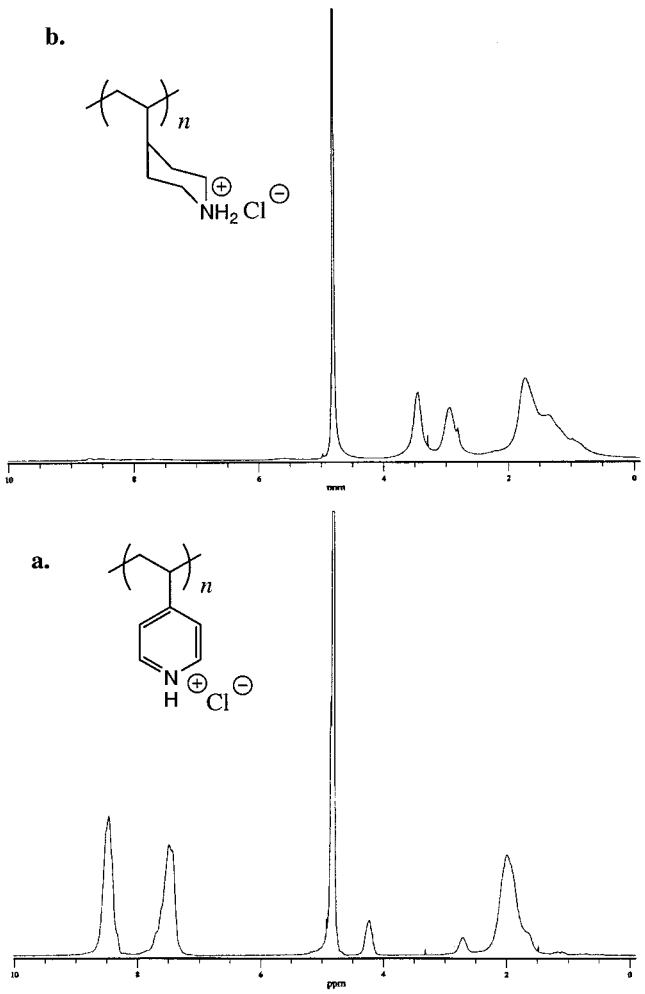


Figure 1. (a) ^1H NMR spectra (D_2O, δ = 4.80 ppm) of 2-PVP·HCl before hydrogenation and (b) 2-PVPip·HCl after hydrogenation.

Heterogeneous catalysts proved far more promising. Pyridine can be hydrogenated using a number of different heterogeneous catalysts including PtO_2, Pt/C, RuO_2, Rh/C, and Pd/C.[15] For example, neat pyridine can be fully hydrogenated to piperidine using Rh/C at 40 °C and 40 psi of H_2 in about 75 h. Consistent with this small molecule model study, we have found that the polymeric pyridine rings can be successfully hydrogenated albeit at higher pressures and temperatures. The percent hydrogenation is determined by monitoring the loss of the aromatic protons in the ^1H NMR (Figure 1).

Part of the rate differential between pyridine and PVP can be simply attributed to the concentration differences—rather than hydrogenations of a neat substrate, the PVP hydrogenations were performed in DMAc (ca. 1 wt % solutions). Fortuitously, the saturated

[†] University of Massachusetts.
[‡] North Carolina State University.

10.1021/ma011013f CCC: $20.00
Published on Web 08/18/2001

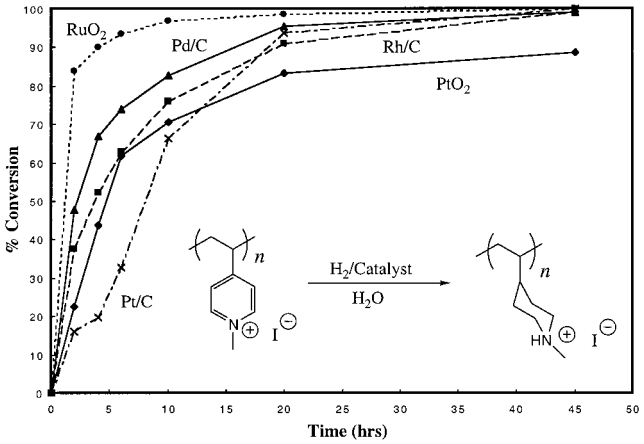


Figure 2. Hydrogenation of poly(*N*-methyl-4-vinylpyridinium chloride) in water (1500 psi, 150 °C).

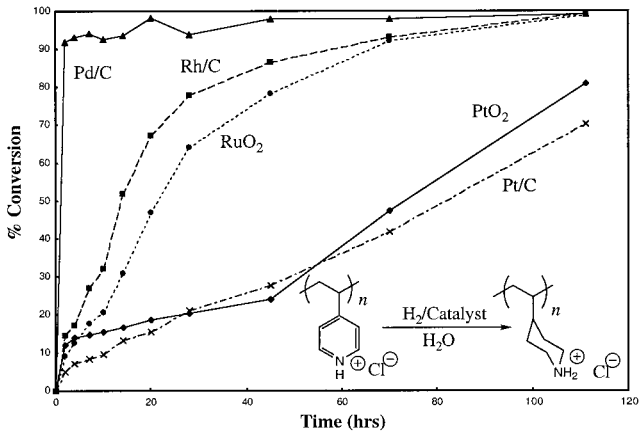


Figure 3. Hydrogenation of poly(4-vinylpyridinium chloride) in water (1500 psi, 150 °C).

poly(vinylpiperidine) (PVPip) proved to be fully soluble in this solvent. Of the two isomeric PVPs, 2-PVP undergoes hydrogenation in a more facile manner. In comparative controls with the monomers, 2-VP was fully hydrogenated after 72 h at 130 °C and 300 psi of H_2, whereas 4-VP required 180 h to reach 97% conversion under identical conditions. Increasing the pressure to 600 psi decreased the reaction time to about 1 day for full saturation of 2-VP.

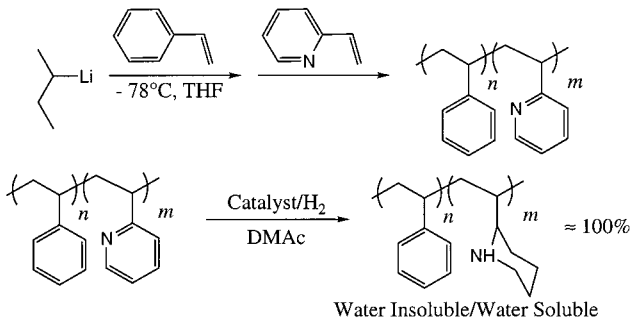
Although the fully saturated polymers could be prepared, this system was less than optimal. Severe catalyst poisoning occurred which was only remedied by the use of large quantities of catalyst. A reasonable assumption is that the pyridine and product piperidine nitrogen coordinate to and poison the catalyst centers. This model is consistent with 2-PVP being a more favorable substrate because coordination to the metal center will be inhibited by the bulk of the adjacent polymer chain. Also, once hydrogenated, we found that the polymer adhered strongly to the supports (e.g., SiO_2 or carbon) and was difficult to remove.

One approach to eliminating the unfavorable N-coordination of the pyridine rings to the catalyst is to alkylate the nitrogens. In fact, the hydrogenation of alkylpyridinium polymers has been reported previously.[16] We too found that the more basic tertiary amine polymers (e.g., poly(*N*-methylvinylpiperidine)) can be prepared by hydrogenation of the corresponding *N*-alkylpyridinium salt. We found that a number of heterogeneous catalysts could be used for the formation of the 3° amine product. In this case, RuO_2 proved to be the most active catalyst (Figure 2).

To prepare the saturated 2° amine polymer, we found we could protonate the pyridine ring before hydrogenation. In acidic aqueous solution the complete hydrogenation of the pyridines to the piperidines could be accomplished in a relatively rapid fashion.[17] Figure 3 shows the kinetic profile for this hydrogenation using five different catalysts.

Some of the heterogeneous catalysts proved quite active under these conditions, e.g., Pd/C, which gave the fully saturated PVPip in just a few hours. The protonated PVPip can be easily isolated by filtration and removal of the water and converted to the free amine by treatment with an ion exchange column (Dowex 550A). Interestingly, the neutralized PVPip proved to be soluble in neutral water. In fact, PVPip powders are so hygroscopic they are deliquescent (i.e., they become a solution by absorbing so much water from the atmosphere). Their water solubility and deliquescent nature are quite surprising given the fact that the carbon-to-nitrogen ratio of this polymer is 7.

Scheme 1



Analyzing for chain degradation during hydrogenation proved difficult for the homo-PVPip materials because they adhered very strongly to and would not elute from the GPC columns. However, molecular weight analysis of hydrogenated block copolymers showed no loss of molecular weight occurred during these hydrogenation (vide infra).

Block copolymers possessing vinylpyridine segments can also be hydrogenated. If the other segment is also unsaturated (e.g., butadiene or styrene), then the opportunity for selective hydrogenation presents itself. For example, we prepared a 50/50 mol % block copolymer of styrene and 2-vinylpyridine using anionic techniques (M_n = 17 400, PDI = 1.19). Selective and quantitative hydrogenation of the 2-PVP block could be accomplished by using the Rh/C catalyst in DMAc, and no hydrogenation of the styrene segment was observed (Scheme 1). Furthermore, the hydrogenated block copolymer could be analyzed using GPC with DMF as a mobile phase,[18] and the measured molecular weight (M_n = 17 800, PDI = 1.18) agreed well with the initial molecular weight, indicating that chain degradation of either block did not occur under these conditions.

The selective hydrogenation of the pyridine rings represents the kinetically controlled product because the thermodynamics preferentially favors hydrogenation of the styrene moieties over the pyridines (vide supra). Changing the solvent to 55/45 vol/vol cyclohexane/methanol mixtures, protonating the pyridines, and using PtO_2 as the catalyst gave materials showing 100% hydrogenation of the 2-PVP block and about 60% hydrogenation of the styrene block. We are fully confi-

dent that modest tweaking of the parameters will yield fully saturated block copolymers.

Identifying conditions for the selective hydrogenation of the styrene ring over the pyridine ring has been slow. Hydrogenation of the styrene is favored thermodynamically, but the kinetics of the pyridine hydrogenation is faster. To circumvent this kinetic bias, we have been exploring running the hydrogenation of the pyridinium−styrene block copolymers under emulsion conditions (mixed chloroform/methanol solutions) which places the pyridine segments in the core and the styrene as a surrounding corona that is accessible to the catalyst. Under these conditions, up to 13% hydrogenation of the styrene without hydrogenation of the pyridine has been achieved. Refinements in this strategy are currently in progress.

In summary, the facile and complete hydrogenation of polymers possessing pyridine moieties can be accomplished in reasonable reaction times and conditions. Furthermore, the pyridine segments of block copolymers of styrene and vinylpyridine can be selectively hydrogenated. The resulting PVPip is deliquescent and soluble in neutral water. Thus, this simple process represents a viable route for augmenting the properties of polymers, and its application in a number of areas is currently being explored.

Acknowledgment. The authors acknowledge the NSF (DMR) for financial support of this work.

References and Notes

(1) (a) March, J. *Advanced Organic Chemistry*, 4th ed.; John Wiley & Sons: New York, 1992. (b) Furniss, B. S.; Hannaford, A. J.; Smith, P. W. G.; Tatchell, A. R. *Vogel's Textbook of Practical Organic Chemistry*, 5th ed.; John Wiley & Sons: New York, 1989.

(2) Stryer, L. *Biochemistry*, 2nd ed.; W. H. Freeman: San Francisco, 1981.

(3) Badesso, R. J.; Nordquist, A. F.; Pinschmidt, R. K.; Sagl, D. J. In *Hydrophobic Polymers*; Glass, J. E., Ed.; Advances in Chemistry Series 248; American Chemical Society: Washington, DC, 1996.

(4) An early attempt to hydrogenate poly(vinylpyridines) was reported in 1957. The conditions were harsh (3500 psi and 220−250 °C), and polymer chain degradation occurred. Also, the isolated material had different physical characteristics than our materials (e.g., water insolubility). See: Katchalsky, A.; Rosenheck, K.; Altmann, B. *J. Polym. Sci.* **1957**, *23*, 955.

(5) (a) Luxton, A. R.; Quig, A.; Delvaux, M.-J.; Fetters, L. J. *Polymer* **1978**, *19*, 1320. (b) Meverden, C. C.; Hogen-Esch, T. E. *Makromol. Chem., Rapid Commun.* **1984**, *5*, 749. (c) Krasnoselskaya, I. G.; Erussalimsky, B. L. *Acta Polym.* **1986**, *37*, 72. (d) Meverden, C. C.; Hogen-Esch, T. E. *J. Polym. Sci., Polym. Chem. Ed.* **1985**, *23*, 159. (e) Mueller, M.; Lenz, R. W. *Makromol. Chem.* **1989**, *190*, 1153.

(6) Ghesquiere, D.; Morcellet-Sauvage, J.; Loucheux, C. *Macromol. Synth.* **1982**, *8*, 79.

(7) Xia, J.; Zhang, X.; Matyjaszewski, K. *Macromolecules* **1999**, *32*, 3531.

(8) Carlini, C. *J. Polym. Sci., Polym. Chem. Ed.* **1980**, *18*, 799.

(9) James, B. R. *Homogeneous Hydrogenation*; John Wiley & Sons: New York, 1973; pp 280−281.

(10) Vollhardt, K. P. C. *Organic Chemistry*; W. H. Freeman and Company: New York, 1987.

(11) (a) Rosedale, J. H.; Bates, F. S. *J. Am. Chem. Soc.* **1988**, *110*, 3542. (b) Bates, F. S.; Rosedale, J. H.; Bair, H. E.; Russell, T. P. *Macromolecules* **1989**, *22*, 2557.

(12) (a) Hucul, D. A.; Hahn, S. F. US Patent 5,612,422, 1997. (b) Zhao, J.; Hahn, S. F.; Hucul, D. A.; Meunier, D. M. *Macromolecules* **2001**, *34*, 1737. (c) Hucul, D. A.; Hahn, S. F. *Adv. Mater.* **2000**, *12*, 1855. (d) Gehlsen, M. D.; Weimann, P. A.; Bates, F. S.; Harville, S.; Mays, J. W.; Wignall, G. D. *J. Polym. Sci., Polym. Phys.* **1995**, *33*, 1527. (e) Gehlsen, M. D.; Bates, F. S. *Macromolecules* **1993**, *26*, 4122.

(13) (a) Otsuki, T.; Goto, K.; Komiya, Z. *J. Polym. Chem., Polym. Chem. Ed.* **2000**, *38*, 4661. (b) Harwood, H. J.; Jolly, S. W. US Patent 5,597,875, 1997. (c) Iio, A.; Oshima, N.; Ohira, Y.; Sakamoto, M.; Oka, H. US Patent 5,202,388, 1993.

(14) (a) McQuillin, F. J. *Homogeneous Hydrogenation in Organic Chemistry*; D. Reidel: Dordrecht, 1976; Chapter 5. (b) Fish, R. H.; Tan, J. L.; Thormodsen, A. D. *Organometallics* **1985**, *4*, 1743. (c) Fish, R. H.; Baralt, E.; Smith, S. J. *Organometallics* **1991**, *10*, 54. (d) Chin, C. S.; Park, Y.; Lee, B. *Catal. Lett.* **1995**, *31*, 239.

(15) (a) Freifelder, M. *Practical Catalytic Hydrogenation*; Wiley-Interscience: New York, 1971; pp 582−601. (b) Rylander, P. N. *Catalytic Hydrogenation in Organic Syntheses*; Academic Press: New York, 1979; Chapter 12. (c) Hegedus, L.; Hada, V.; Tungler, A.; Mathe, T.; Szepesy, L. *Appl. Catal. A* **2000**, *201*, 107.

(16) Sowers, E. E.; Goe; G. L.; Prunier, M. L. US Patent 4,413,-099, 1983.

(17) A typical procedure for the hydrogenation of 4-PVP follows: 4-PVP (3 g, Aldrich, $M_w = 60\,000$) was protonated by dissolving in 100 mL of methanol and adding HCl (6 mL, 7.3 M). After stirring for 2 h the solvent was removed under vacuum. To a 20 mL glass vial were added protonated 4-PVP (0.2 g), water (10 mL), Pd/C (0.2 g, 5 wt %), and a magnetic stir bar. The charged vial was placed in a 300 mL stainless steel autoclave that was then charged with H_2 and heated to 150 °C with stirring at a total pressure 1500 psi. After 4 h the reaction was stopped, the reaction mixture filtered and the solvent removed under vacuum to yield a white powder. ^{1}H NMR (300 MHz, D_2O): δ (ppm) 1.72 (8H), 2.93 (2H), 3.44 (2H). Anal. Calcd for $C_7H_{14}NCl$: C, 56.9; H, 9.5; N, 9.5; Cl, 24.1. Found: C, 56.71; H, 9.24; N, 8.17; Cl, 21.65.

(18) Molecular weight and molecular weight distributions were measured via gel permeation chromatography using a Jasco PU-1580 pump and a Jasco RI-1530 refractive index detector at a flow rate of 1 mL/min at room temperature. The stationary phase consisted of two PL-Gel mixed C columns and 0.1% (w/v) tetrabutylammonium bromide in dimethylformamide (DMF) was used as the mobile phase. Molecular weights are relative to narrow molecular weight polystyrene standards (Pressure Chemical, Inc.).

MA011013F