Reversible and irreversible conformational changes in poly(isocyanide)s: a remote stereoelectronic effect†

David B. Amabilino,[*a] **José-Luis Serrano**[b] **and Jaume Veciana**[a]

**Poly(isocyanide)s prepared by diastereoselective polymerisation of two chiral monomers, which differ only in the presence of a nitro-group adjacent to the stereogenic group, exhibit long range chiral induction, but a surprising influence of a remote substituent on the conformation and stability of the secondary structure in the macromolecules.**

The chiral secondary structures adopted by poly(isocyanide)s[1] have been the source of much interest[2] and debate[3] for decades. The conformations of the polymers are important for the properties that they exhibit.[4] Up to now, polymerisation of chiral aromatic isocyanides has resulted in macromolecules with stable chiral conformations. One of our interests is to study these secondary structures and the effects that changes in monomer structure have on them. Our curiosity was aroused when the polymerisation of the isocyanide (*R*)-**1** afforded poly(isocyanide) (*R*)-**2** which shows optical activity indicative of long-range chiral induction from the stereogenic centre to the growing polymer backbone.[5] The chiral induction is determined kinetically through steric effects, with non-covalent interactions between growing polymer and incoming monomer playing a role.[5] Here, we demonstrate that the conformational stability of the chiral secondary structures of polymers of the type (*R*)-**2** can be significantly altered by a relatively small structural change close to the stereogenic centre, as in (*R*)-**4**.

The polymer (*R*)-**4** was prepared (Scheme 1) by DCC coupling of the chiral phenol (*R*)-**5** (synthesised using a similar route to related compounds[6,7]) with 4-formamidobenzoic acid, affording the formamide (*R*)-**6** which was dehydrated with diphosgene to give the isocyanide (*R*)-**3** whose polymerisation was catalysed with NiCl₂.6H₂O. The polymer (*R*)-**2** was prepared using an analogous route, as reported in ref. 5. The polymers were characterised by IR and NMR spectroscopy, by gel permeation chromatography (GPC), and circular dichroism (CD) spectroscopy.

The IR spectra of the polymers (*R*)-**2** and (*R*)-**4** show the same characteristic band at approximately 1650 cm^{-1} corresponding to the C=N bond. The ^{1}H and ^{13}C NMR spectra are also similar. The ^{1}H NMR spectra are extremely broad, with two of the aromatic proton resonances appearing below 6 ppm, indicating proximity of the aromatic rings. On the whole, the ^{13}C NMR spectra of (*R*)-**4** is similar to that of (*R*)-**2**, with relatively sharp resonances arising from the carbon atoms of the alkyl chain and broad or very broad resonances assigned to the aromatic resonances. However, in the region of the iminomethyl resonance (*R*)-**4** reveals a quite broad
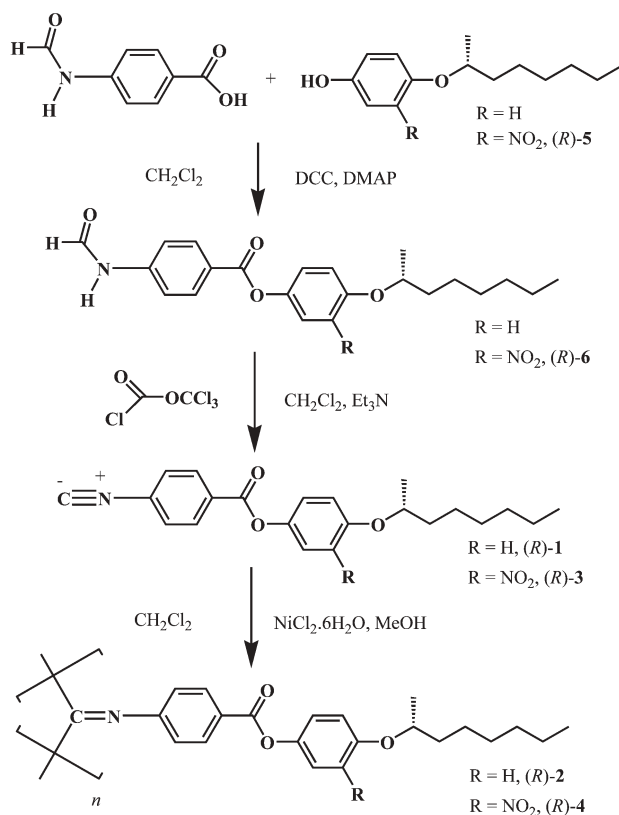
Scheme 1 Synthesis of polymers (*R*)-**2** and (*R*)-**4**.

and poorly defined signal, while that of (*R*)-**2** shows two relatively sharp resonances (see electronic supplementary information, ESI†). This observation hints at a difference in backbone structure between the two compounds.

The molecular weights and polydispersities of the polymers determined by GPC in THF are practically identical (the $\bar{M}_n$ of (*R*)-**4** is 33 kDa and $\bar{M}_w$ is 82 kDa, with a polydispersity index of about 2.5), as was to be expected, since the reactivity of the isocyanide groups in the monomers has to be similar.

The CD spectra of the polymer (*R*)-**2** in THF at various temperatures are shown in Fig. 1. It shows the Cotton effects typical of chiral aromatic poly(isocyanide)s, with maxima at 363 and 252 nm.[5,8] For this (*R*) enantiomer these effects are positive and negative, respectively. As the temperature of the solution is increased, there is a slight decrease in the magnitude of the Cotton effects, but this change is completely reversible in the temperature range studied. When the CD spectrum was recorded at 25 °C, the sample cooled to 0 °C then warmed to 55 °C, held for 30 minutes,
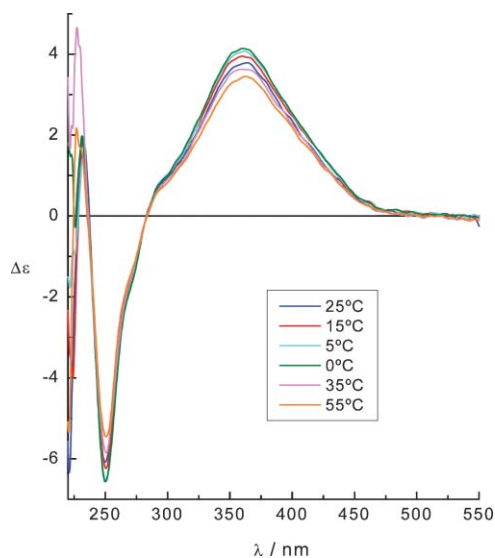
Fig. 1 Variable temperature CD spectra of (*R*)-**2** in THF.

and returned to 25 °C, the CD spectrum was absolutely identical. This observation is consistent with a rigid secondary structure, that largely accepted for the poly(isocyanide)s, which "breathes" upon heating and cooling.

In stark contrast to polymer (*R*)-**2**, polymer (*R*)-**4** does not show the typical CD spectrum of a chiral aromatic poly(isocyanide). Rather, a very weak negative Cotton effect is observed at around 360 nm, followed by a strong positive signal at 283 nm, and a further strong negative Cotton effect at 252 nm (Fig. 2). The monomer shows a negligible optical activity in these areas, and therefore the chirality has been amplified during the polymerisation. However, the position of the Cotton effects strongly suggest that the secondary structure of this polymer is not the usual one in this family of macromolecules.

Furthermore, (*R*)-**4** displays a dramatic and irrecoverable loss of optical activity associated with a low thermodynamic stability of
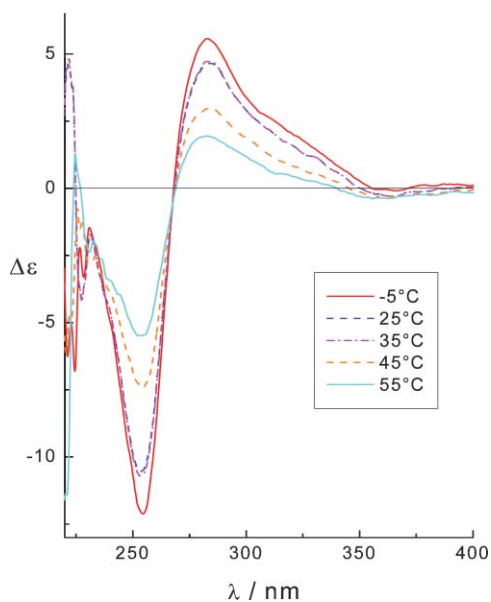

Fig. 2 Variable temperature CD spectra of (*R*)-**4** in THF.

the chiral conformation generated during its synthesis. When a THF solution of the polymer was cooled to 5 °C, a slight increase of the optical activity was observed, implying the kind of behaviour exhibited by (*R*)-**2**. However, warming the solution up to 55 °C resulted in a striking decrease in the intensity of the Cotton effects, which was irreversible when the solution was cooled back to 25 °C.

When a THF solution of (*R*)-**4** was maintained at 55 °C for 2.5 h a gradual loss of optical activity was observed. The Cotton effects at 283 and 252 nm after 30 min have molar absorptivities of 2.00 and −5.40, respectively, while at the end of the period they are 1.16 and −4.23, respectively. There were no detectable changes in the UV-vis absorption spectra, and the ^{13}C NMR spectra before and after heating are identical, so there seems to be no chemical change.

All this data implies that an irreversible conformational change of the polymer backbone takes place in which the kinetically determined chiral secondary structure adopted during the course of the polymerisation of the precursor monomer is lost to diastereomeric conformations that cannot revert back to the original optically active one. This situation is not in accord with a stable helical form, almost certainly determined by the conformation that the 2-octyl chain is forced to adopt in the presence of the nitro group at the 2-position relative to it, and may even be related with the dipole moment associated with this conformation.[9]

While the kind of irreversible conformational change presented by the polymer is not unique,[10] it is the first observation of this kind of behaviour in aromatic poly(isocyanide)s, and is indicative of a metastable secondary structure, and confirms that the as-formed poly(isocyanide) is a kinetically-determined product.

The results presented show how a remote stereoelectronic effect, the slight change introduced by the presence of the nitro group located about 10 Å away from the isocyanide carbon atom in the monomer, can dramatically change not only the secondary structure of the polymer, but also its conformational stability.

David B. Amabilino,[*a] **José-Luis Serrano**[b] **and Jaume Veciana**[a]
[a]*Institut de Ciència de Materials de Barcelona (CSIC), Campus Universitari, 08193-Bellaterra, Catalonia, Spain.*
E-mail: amabilino@icmab.es; Fax: +34 93 580 5729; Tel: +34 93 580 1853
[b]*Instituto de Ciencia de Materiales de Aragón (CSIC), Universidad de Zaragoza, 50009, Zaragoza, Spain. E-mail: joseluis@unizar.es;*
Fax: +34 976 761209; Tel: +34 976 761209

Notes and references

1 F. Millich, *J. Polym. Sci., Macromol. Rev.*, 1980, **15**, 207; R. J. M. Nolte, *Chem. Soc. Rev.*, 1994, **23**, 11; J. J. L. M. Cornelissen, A. E. Rowan, R. J. M. Nolte and N. A. J. M. Sommerdijk, *Chem. Rev.*, 2001, **101**, 4039.

2 A. J. M. van Beijnen, R. J. M. Nolte, W. Drenth and A. M. F. Hezemans, *Tetrahedron*, 1976, **32**, 2017; A. J. M. van Beijnen, R. J. M. Nolte, A. J. Naaktegeboren, J. W. Zwikker, W. Drenth and A. M. F. Hezemans, *Macromolecules*, 1983, **16**, 1679; P. C. J. Kamer, R. J. M. Nolte and W. Drenth, *J. Am. Chem. Soc.*, 1988, **110**, 6818–6825; P. C. J. Kamer, M. C. Cleij, R. J. M. Nolte, T. Harada, A. M. F. Hezemans and W. Drenth, *J. Am. Chem. Soc.*, 1988, **110**, 1581–1587;

D. B. Amabilino, E. Ramos, J.-L. Serrano and J. Veciana, *Adv. Mater.*, 1998, **10**, 1001; Y. Yamada, T. Kawai, J. Abe and T. Iyoda, *J. Polym. Sci. A, Polym. Chem.*, 2002, **40**, 399.

3 M. M. Green, R. A. Gross, F. C. Schilling, K. Zero and C. Crosby, III, *Macromolecules*, 1988, **21**, 1839; D. Pini, A. Iuliano and P. Salvadori, *Macromolecules*, 1992, **25**, 6059; M. Clericuzio, G. Alagona, C. Ghio and P. Salvadori, *J. Am. Chem. Soc.*, 1997, **119**, 1059; L. Spencer, M. Kim, W. B. Euler and W. Rosen, *J. Am. Chem. Soc.*, 1997, **119**, 8129; F. Takei, H. Hayashi, K. Onitsuka, N. Kobayashi and S. Takahashi, *Angew. Chem., Int. Ed. Engl.*, 2001, **40**, 4092; M. Ishikawa, K. Maeda and E. Yashima, *J. Am. Chem. Soc.*, 2002, **124**, 7448.

4 M. N. Teerenstra, R. D. Klap, M. J. Bijl, A. J. Schouten, R. J. M. Nolte, T. Verbiest and A. Persoons, *Macromolecules*, 1996, **29**, 4871; M. N. Teerenstra, J. G. Hagting, A. J. Schouten, R. J. M. Nolte, M. Kauranen, T. Verbiest and A. Persoons, *Macromolecules*, 1996, **29**, 4876.

5 E. Ramos, J. Bosch, J.-L. Serrano, T. Sierra and J. Veciana, *J. Am. Chem. Soc.*, 1996, **118**, 4703; D. B. Amabilino, E. Ramos, J.-L. Serrano, T. Sierra and J. Veciana, *J. Am. Chem. Soc.*, 1998, **120**, 9126.

6 M. Trollsås, C. Orrenius, F. Sahlén, U. W. Gedde, T. Norin, A. Hult, D. Hermann, P. Rudquist, L. Komitov, S. T. Lagerwall and J. Lindström, *J. Am. Chem. Soc.*, 1996, **118**, 8542.

7 M. Svensson, B. Helgee, K. Skarp and G. Andersson, *J. Mater. Chem.*, 1998, **8**, 353.

8 F. Takei, H. Hayashi, K. Onitsuka and S. Takahashi, *Polym. J.*, 2001, **33**, 310; N. Hida, F. Takei, K. Onitsuka, K. Shiga, S. Asaoka, T. Iyoda and S. Takahashi, *Angew. Chem., Int. Ed. Engl.*, 2003, **42**, 4349; M. Ishikawa, K. Maeda, Y. Mitsutsuji and E. Yashima, *J. Am. Chem. Soc.*, 2004, **126**, 732.

9 D. M. Walba, M. B. Ros, N. A. Clark, R. Shao, M. G. Robinson, J.-Y. Liu, K. M. Johnson and D. Doroski, *J. Am. Chem. Soc.*, 1991, **113**, 5471.

10 J. Q. Nguyen and B. L. Iverson, *J. Am. Chem. Soc.*, 1999, **121**, 2639.