Orientational Properties of Poly-γ-benzyl-L-glutamate: Influence of Molecular Weight and Solvent on Order Parameters of the Solute

Andreas Marx and Christina Thiele*[a]

Abstract: Residual dipolar couplings (RDCs) have recently become increasingly important in organic structure determination due to their unique information content. One main limitation for the use of RDCs in organic compounds, however, is that the compound in question needs to be oriented with respect to the magnetic field in order to measure RDCs. So far, there are very few possibilities for modulating the induced degree of orientation. The situation is even worse when chiral orienting media are considered, which could allow absolute configuration determination in the future. We have conducted a systematic investigation into modulating the orientation induced by one chiral orienting medium, namely organic solutions of PBLG (poly-γ-benzyl-L-glutamate), as a function of its molecular weight and the organic co-solvent used, and have obtained significant insights into factors that influence the order induced. With increasing molecular weight of the polypeptide the orientation of the solutes decreases, leading to well-resolved spectra with improved line shapes. This can be attributed exclusively to the fact that the critical concentration of the liquid-crystalline phase decreases with increasing molecular weight (pure dilution effect). Any influence of increasing flexibility on the orientation can be ruled out.

Keywords: enantiodiscrimination · NMR spectroscopy · peptides · polymers · residual dipolar coupling

Introduction

Although NMR spectroscopy in ordered media (alignment media) has been used since 1963,[1–4] applications of dipolar couplings in organic structure determination are still rather scarce.[5,6] This is due to the high degree of solute orientation induced by most applied liquid-crystalline (LC) phases, which dominate the spectra (D≫J, strong alignment) and quickly result in spectra too complex to be interpreted by the non-specialist. Applications of dipolar couplings have therefore, until recently, been limited to small, mostly symmetric compounds. Lately, impressive studies partly using sophisticated computer programs for spectral assignments have appeared, making full use of all the obtainable information from dipolar couplings.[7–9]

With the advent of orienting media (diluted lyotropic LC phases with water as co-solvent),[10–16] which induce a low degree of orientation, the observed dipolar couplings could be scaled down from many kHz to a few Hz (weak alignment),[17,18] then called residual dipolar coupling (RDC). These media are water-based orienting media suitable for the orientation of biomolecular macromolecules. They are, however, not suitable for use with most water-insoluble organic compounds.

It has been shown that if suitable orientation of the organic compound in question can be achieved, RDCs yield information complementary to the distance information obtained from the NOE[19] or angular information from J couplings[20] or cross-correlated relaxation,[21–23] even allowing the determination of the relative configuration in (moderately) flexible compounds.[6,24]

One of the crucial limiting factors in using RDCs for organic structure determination is the availability of organic-solvent-based orienting media inducing a small degree of order. So far, there are two main methods: strain-induced alignment in a gel (SAG)[25–31] and LC phases. The main advantage of the former technique is that it allows, in principle, an unrestricted scaling of the orientational order over a wide range by use of different degrees of cross-linking of

[a] Dipl.-Chem. A. Marx, Dr. C. M. Thiele
Technische Universität Darmstadt
Clemens Schöpf Institut für Organische Chemie und Biochemie
Petersenstr. 22, 64287 Darmstadt (Germany)
Fax: (+49)341-165-531
E-mail: cmt@punk.oc.chemie.tu-darmstadt.de

the gel. One major drawback, however, is that so far, no chiral, organic, solvent-based cross-linked gel is available.

The second, conceptually different method for partial alignment is the use of organic-solvent-based LC phases; these, however, often orient too strongly. So far, only lyotropic LC phases made of dilute solutions of homo-polypeptides, namely poly-γ-benzyl-ʟ-glutamate (PBLG), poly-γ-ethyl-ʟ-glutamate (PELG), and poly-ε-carbobenzyloxy-ʟ-lysine (PCBLL) have proven to be suitable LC media for the orientation of organic compounds.[32–48] The main advantages are their ready availability (commercial suppliers) and chemical inertness. Another advantage is the chirality of the LC phases made of homo-polypeptides, which forms the basis for the impressive work on enantiodiscrimination done by the Courtieu and Lesot group.[38–48] Besides enantiodiscrimination, the chirality of the LC phase would, in principle, allow the determination of the absolute configuration without any derivatisation if the interaction of solute and liquid crystal were known precisely. A first result in this field, based on comparison of a chiral compound of unknown configuration with chemically similar compounds of known configuration, has been reported by Lesot et al.[49] The main disadvantage of the LC-based strategy of orienting compounds is the necessity of a minimum concentration in order for the LC phase to be formed, resulting in a minimum anisotropy, which can only be dropped further by applying variable angle sample spinning (VASS).[50,51]

PBLG was the first synthetic polymer to exhibit an LC phase,[52] and due to its good solubility in many organic solvents, it has become a standard when LC polymers are considered. In many organic solvents it adopts an α-helical structure, making it also a standard when model compounds for α-helices are required. PBLG is well investigated and has widespread applications, but so far little is known about its potential as an orienting medium for the measurement of RDCs and the possibilities for influencing orientational order and preferred orientation.[53] We[33] and others[34,41–43,54] have applied PBLG LC phases for measuring RDCs. The order induced in commercial PBLG, however, is often too high, leading to complications in the interpretation of spectra.

Since information about factors modulating the degree of order and the preferred orientation introduced are sparse, we have started a systematic investigation into the factors influencing the orienting properties of PBLG, the two most obvious being its molecular weight and the solvent used.

For the applicability of PBLG LC phases, the induced degree of order, which can be described by an order parameter, should be scalable over a wide range. It is known that the order parameter of the PBLG LC phase is closely related to the volume fraction of PBLG.[55,56] Furthermore, for rod-like molecules like PBLG it is known that the concentra-

tion range in which the LC phase is stable widens with increasing axial ratio L/D (in which L is the length of the rod and D its corresponding diameter) and thus with increasing molecular weight (MW) as D stays constant.[55,57,58] From the results of DuPré et al. it can be anticipated that this is true only when L is smaller than the persistence length (P) of the polymer $(L < P)$.[59] Persistence lengths reported for PBLG, however, vary significantly in the literature (70–150 nm). Starting from this point, we synthesised several PBLGs with various chain lengths (axial ratios) and investigated the orientational properties of isopinocampheol (IPC) as the solute.

Results and Discussion

Synthesis of PBLGs of different MW: PBLG was synthesised by ring-opening polymerisation of the corresponding N-carboxyanhydride (NCA). Out of the three possible methods[60] we used the living polymerisation catalysed by transition metals (Deming protocol),[61–63] as it has several advantages over the two conventional methods using initiation by bases or nucleophiles. It allows controlled polymerisation of both low- and high-MW polymers with narrow molecular weight distributions (MWD) simply by choice of the ligand attached to the metal centre or the solvent.

The monomer **3** was synthesised by adapted procedures from Albert et al.[64] and Goodman et al.[65] as depicted in Scheme 1. In the first step, ʟ-glutamic acid **1** is reacted with benzyl alcohol in the presence of two equivalents of tetrafluoroboric acid (HBF₄) to exclusively give the γ-ester **2**. The NCA **3** is obtained by reaction of **2** with phosgene in dry THF.

Table 1 shows selected samples of PBLG covering a broad range of MW, and hence axial ratios, of the resulting α-helical rodlike polymers. In Table 1, the number averaged MWs (M_n) and the molecular weight distributions (MWDs) are reported, which were determined by gel permeation chromatography (GPC) against polystyrene standard samples (for more details see Experimental Section). All entries in Table 1 were synthesised by the Deming protocol except sample **4b**, which is a commercial sample (Sigma–Aldrich). The rather broad MWDs are unusual, since the polymerisation has living character. To date, we cannot exclude the possibilities that the broad MWD might be either an artefact (adsorption phenomenon onto the stationary phase) from the gel permeation chromatography (GPC), since the
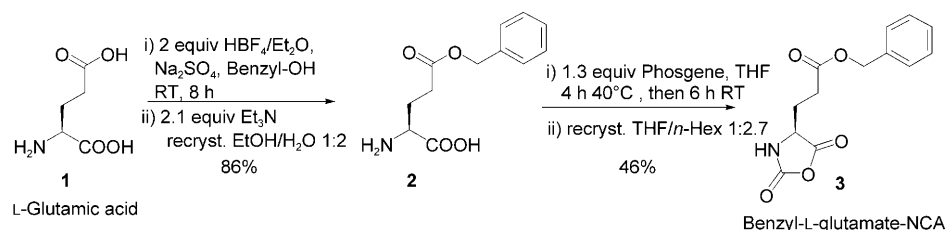
Scheme 1. Synthesis of monomer **4** by adopted procedures of Albert et al.[64] and Goodman et al.[65]

Table 1. PBLGs of different MW synthesised using the Deming protocol.[61–63]

$$3 \xrightarrow[\text{THF, RT}]{[\text{Ni(cod)X}]} \text{PBLG } 4$$

PBLG	X	$[M]/[I]$[a]	M_n[b] [g mol^{-1}]	MWD	Yield [%]
4a	bpy[c]	50:1	20100	2.28	71
4b[d]	–	–	32000	3.41	–
41c	bpy	75:1	58000	2.91	74
4d	tmeda[e]	100:1	106000	1.65	72
4e	dmpe[f]	125:1	167000	1.66	85
4f[g]	dmpe	150:1	384000	2.97	97
4g	tmeda	200:1	404000	2.22	85
4h[g]	tmeda	200:1	602000	2.57	84

[a] Monomer-to-initiator ratio. [b] Number averaged molar mass, $M_n = \Sigma x_i M_i$ (for $i = 1 \rightarrow n$), with x_i as the mole fraction of M_i, and M_i as the molar mass of the i-mer. [c] 2,2′-Bipyridine. [d] Sample from commercial supplier (Sigma–Aldrich). [e] $N,N,N′,N′$-Tetramethylethylendiamine. [f] Bis(dimethylphosphino)ethane. [g] Not living throughout polymerisation time, as indicated by decolourisation of the reaction solution.

peaks show pronounced tailing, or a result of small impurities in the monomer leading to partial abortion of the living polymerisation. We have not observed any influence of the MWD (in the region of the samples synthesised by us) on the line width of the NMR signals and hence on the resolution of spectra.

Dependence of the degree of order on MW as monitored by $\Delta\nu_Q$: As shown by Samulski et al.,[66,67] the quadrupolar splitting ($\Delta\nu_Q$) can be used as an indicator for the degree of order of the LC phase. It should be emphasised, however, that it is only a qualitative measure for the order induced in the solute. There is no direct connection between the absolute degree of orientation and $\Delta\nu_Q$, as shown, for example, by comparison of the orientational properties of strychnine in PELG and PBLG, for which at the same $\Delta\nu_Q$ the values of the RDCs were significantly lower (by a factor of ≈ 3) in PELG.[35]

As clearly seen when comparing the entries in Table 2, the critical concentration of the LC phase, that is, the concentration at the phase boundary between the stable LC phase and the LC/isotropic biphasic region (as monitored by recording ^{2}H spectra), decreases with increasing MW. The effect is much more pronounced in the low-MW region, for which a steep decrease is present, whereas in the high-MW region the critical concentration asymptotically approximates to a final value (this behaviour is in accordance with observations reported by Robinson et al.[58] for entrance of birefringence). From the good qualitative agreement of our results with the theoretical predictions of DuPré[59] it seems to be a sensible assumption that the length L of the high-MW PBLGs (**4f–i**) is larger than the persistence length P of the polymer ($L > P$).

The absolute value of the minimal quadrupolar splitting ($|\Delta\nu_{Q,min}|$), that is, the quadrupolar splitting of the [D$_1$]chloroform signal at the critical concentration, shows identical behaviour (Figure 1). Table 2 clearly shows the concentration dependence of $|\Delta\nu_{Q,min}|$, with $|\Delta\nu_{Q,min}|$ ap-

Table 2. Selected examples of PBLG with various MWs and their corresponding minimal quadrupolar splittings at the critical concentration of the LC phase at 303 K.

PBLG	M_n[a] [g mol^{-1}]	MWD	L[b] [nm]	(w/w)[c] [%]	$\lvert\Delta\nu_{Q,min}\rvert$[d] [Hz]	$\Delta\nu_{1/2}$[e] [Hz]
4a	20100	2.28	12	19.8	828	22.0
4b[f]	32000	3.41	20	12.0	407	5.8
4c	58000	2.91	36	9.7	301	5.7
4d	106000	1.65	65	8.5	243	7.2
4e	167000	1.66	104	8.6	246	5.6
4f	384000	2.97	237	7.3	192	4.6
4g	404000	2.22	249	7.0	180	2.2
4h	602000	2.57	372	6.2	170	11.7

[a] Number averaged molar mass, $M_n = \Sigma x_i M_i$ (for $i = 1 \rightarrow n$), with x_i as the mole fraction of M_i, and M_i as the molar mass of the i-mer. [b] Length of rod-like polymer chain. Calculated using L/monomer = 0.15 nm.[79] [c] Mass concentration of polymer in [D$_1$]chloroform. [d] Absolute value of the minimal quadrupolar splitting, that is, splitting of the deuterium signal of [D$_1$]chloroform (without isotropic signal being present). [e] Peak width at half height of the [D$_1$]chloroform signal. The rather large line width of the samples made out of PBLG **4a** and **4h** might be due to inhomogeneities. [f] Sample from commercial supplier (Sigma–Aldrich).
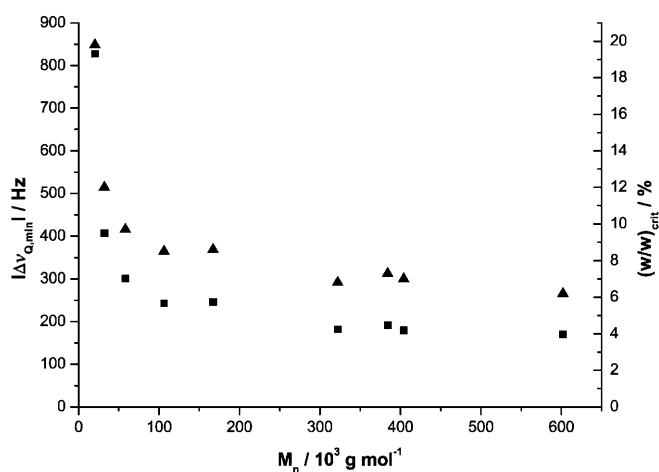

Figure 1. Dependence of the absolute value of the minimal quadrupolar splitting $|\Delta\nu_{Q,min}|$ (■), and the critical concentration of the LC phase (▲, in w/w %) on the MW of PBLG. The measurements were carried out at 303 K with CDCl$_3$ as the organic co-solvent.

proaching a final value of about 170 Hz. By use of very high MW PBLG it was possible to decrease the critical concentration to about 6 % w/w, but due to the asymptotical behaviour of the critical concentration (Figure 1) as a function of MW (in the region $L > P$) no further drop by even higher MW PBLG was possible. If one wanted to reduce $|\Delta\nu_{Q,min}|$ and therefore the degree of orientation of the solute even further other strategies would be required, a subject which we are currently working on.

Orientational properties as studied by the orienting tensor of the solute isopinocampheol (IPC): To study the orientational properties of PBLGs with different MWs, we use IPC as a solute, since it is a rigid compound and provides a sufficiently large number of RDCs to be able to determine

(-)-IPC
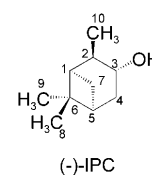
the orienting tensor reliably. All experiments using IPC as solute were carried out slightly above the critical concentration to ensure a stable LC phase. The stability of the LC phase was confirmed by equilibrating the NMR sample in the magnetic field for about 30 min and recording ^2H spectra immediately before and after every HSQC experiment. The orienting tensors were obtained from all extractable $^1D_{CH}$ values using the program PALES.[68] The input geometry for PALES was provided by computing the equilibrium structure of one enantiomer on the density functional theory (DFT) level by using the hybrid functional B3LYP[69] as implemented in the program Gaussion03[70] and employing the 6-311+G(d) basis set. The other enantiomer was obtained by inverting all z coordinates in the coordinate file, leading to an identical initial molecular axis frame. The axis frame in the pdb file was used as the initial molecular axis frame when determining the orienting tensor. Euler angles are reported as z, y', z'' rotations with respect to this molecular axis frame.[71]

The properties of the orienting tensors for (+)-IPC in selected PBLGs of different MW are summarised in Table 3 (for an excellent article describing the properties of the

Table 3. Orienting tensor properties of (+)-IPC in PBLG/CDCl$_3$ LC phases.

PBLG	IPC	$\mid\Delta\nu_Q\mid^{[a]}$ [Hz]	n(RDC)[b]	$D_a^{[c]}$ [10^{-4}]	$R^{[d]}$	$\alpha^{[e]}$	$\beta^{[e]}$	$\gamma^{[e]}$	$R^{2[f]}$
4b[g]	(+)	470	11	10.5	0.57	105	100	140	0.995
4c	(+)	352	11	6.9	0.57	105	101	136	0.993
4f	(+)	218	11	4.7	0.60	106	104	131	0.997

[a] Quadrupolar splitting of the solvent signal in the liquid crystal. [b] Number of $^1D_{CH}$ used for calculation of the parameters D_a, R, α, β, γ with PALES. [c] Axial component of the orienting tensor. [d] Rhombicity. [e] The three Euler angles relating the principle axis system and the initial molecular axis frame. Only one out of the four possible orientations is reported as the remaining three orientations can be constructed by symmetry operations. [f] Correlation factor for fit of calculated versus measured RDCs. [g] Commercially available PBLG from Sigma–Aldrich

alignment/orienting tensor see reference [72]). The absolute value of the axial component of the orienting tensor D_a ($D_a = S_{zz}/2$) is a quantitative measure for the degree of order induced. As seen from Table 3, the absolute value of D_a decreases with decreasing $\Delta\nu_Q$, which demonstrates that not only the order induced in the solvent, but also the degree of order of the solute, is reduced.

By application of very high MW PBLG, it is possible to lower the values of the RDCs to a reasonable order of magnitude of about 10 Hz for IPC. Additionally, due to the diminished degree of orientation, the line widths become significantly smaller (as also ^1H–^1H RDCs decrease significantly) and the line shapes and signal-to-noise ratios are much better (Figure 2). The resolution of the spectra is so good for the very high MW PBLG that all RDCs were extractable from ω_2-coupled HSQC experiments.

The decrease of D_a for the solute at the critical concentration is in clear contrast with the observation reported by Abe et al.[56] for PBLG itself. Abe et al. showed that the
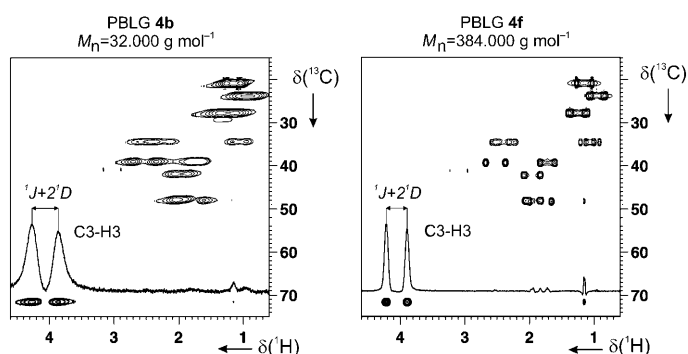

Figure 2. ω_2-coupled HSQCs of (−)-IPC in PBLGs of different MW. The trace of the C3–H3 correlation is extracted to show the improved line-width, signal-to-noise ratio, and resolution for the very high MW PBLG **4f**.

order parameter for PBLG itself (as monitored by deuteration of the polymer backbone) near the critical concentration is independent of the MW (even when $L < P$).

Another very interesting finding is that the three Euler angles (α, β, γ), which define the orientation of the solute with respect to the static magnetic field B_0,[73] are independent of the concentration of the LC phase and the MW of the PBLG (within experimental error). An important conclusion from this finding is that there must be two independent mechanisms of solute orientation, one determining the degree of orientation (concentration dependent) and another one responsible for the orientation itself. First hints in this direction can be found in publications of the Lesot/Courtieu group.[43,47]

The RDCs measured (see the tables in the Supporting Information) for (+)-IPC and (−)-IPC in PBLG are clearly different, thus demonstrating that enantiodiscrimination is taking place (in accordance with the results reported by Courtieu's group[39,42]). Since the orientation of the solute is independent of the concentration and MW of PBLG, the degree of enantiodiscrimination is the same in all experiments. Note, however, that it might be that differences due to chemical shift anisotropy (CSA) are no longer observable, leading to non-resolved lines for the two enantiomers.

Flexibility and concentration dependence of the degree of order: One question may arise: what factors are mainly responsible for the decrease of the order induced (as monitored by D_a)? Is it solely due to the higher dilution of the LC phase or is the increased flexibility of the polymer chain responsible for the diminished degree of orientation? In so-called helicogenic solvents, PBLG has both a rigid backbone and a rather conformationally fixed side chain.[74,75] With increasing axial ratio L/D, the PBLG chain is believed to become more and more flexible, and is treated by theoretical models either as a transition from a rigid rod to a semi-flexible wormlike chain polymer,[76] or by incorporation of some random coil segments leading to an interrupted helical rod.[77] Increased flexibility would result in a broader distribution of orientations of the solute along the polymer chain and hence in a decreased observed degree of orientation.

Table 4. Comparison of the alignment properties of (−)-IPC in PBLGs of different MW.

PBLG	M_n [g mol^{-1}]	$\|\Delta\nu_Q\|$ [a] [Hz]	n(RDC)[b]	D_a[c] [10^{-4}]	R[d]	R^2[e]
4b[f]	32 000	451	11	−8.6	0.65	0.995
4f	384 000	449	11	−8.7	0.64	0.991
4f	384 000	231	11	−4.4	0.47	0.978

[a] Quadrupolar splitting of the solvent signal in the liquid crystal. [b] Number of $^1D_{CH}$ used for calculation of the parameters D_a and R with PALES. [c] Axial component of the orienting tensor. [d] Rhombicity. [e] Correlation factor for fit of calculated versus measured RDCs. [f] Commercially available PBLG from Sigma–Aldrich.

Table 4 shows the order parameters of IPC in PBLGs with different MWs (axial ratios). For entry 1 (PBLG **4b**, $M_n = 32$ kDa) and entry 2 (PBLG **4f**, $M_n = 384$ kDa) the concentration of the LC phase was kept constant, and for entry 3 (PBLG **4f**, $M_n = 384$ kDa) it was slightly diluted. As clearly seen, the increased MW (axial ratio) and therefore also increased flexibility from **4b** to **4f** has no effect on the degree of orientation, at least not a measurable one. This is again in clear contrast with the observation reported by Abe et al.[56] for PBLG itself. Abe et al. reported that for a given concentration the order parameter increases with increasing axial ratio. The slightly diluted LC phase of entry 3 clearly has a lower degree of orientation, as indicated by the drop in D_a. As a consequence, the decrease of D_a is a pure dilution effect.

Solvent dependence: In the next series, we checked the alignment properties of (+)-IPC in different helicogenic solvents (Table 5). Among the tested halogenated solvents, [D$_2$]dichloromethane (CD$_2$Cl$_2$) shows a significantly lower degree of orientation (compared to CDCl$_3$), although the critical concentration for the LC phase is higher. This is rather surprising, as the chemical difference to CDCl$_3$ is very small. The most evident difference is the polarity, which is significantly higher for CD$_2$Cl$_2$. If 1,1,2,2-[D$_2$]tetrachloroethane (C$_2$D$_2$Cl$_4$), which has comparable polarity to CDCl$_3$, is used as the solvent, the critical concentra-

tion and degree of orientation are practically the same as for CDCl$_3$.

When using more polar helicogenic solvents, for example, [D$_8$]THF or [D$_7$]DMF, we expected the effect to be even more pronounced. For [D$_8$]THF this is truly the case, as seen from Table 5; although the critical concentration of the LC phase is twice as high as for CDCl$_3$, the absolute value of D_a is the same. Unfortunately, this trend does not continue with [D$_7$]DMF, although it is by far the most polar solvent. The critical concentration is even higher than for [D$_8$]THF and the value of D_a indicates that the degree of orientation is significantly increased.

The orientation of the solute is nearly the same for all halogenated solvents and changes only slightly for [D$_8$]THF and slightly more for [D$_7$]DMF.[78] This behaviour is quite different from that of the cross-linked polystyrene gels (PS gel) as reported by Luy et al.,[27] in which the solute orientation changes more significantly with the solvent.

Thus it seems to be rather complicated to rationalise the orienting properties of PBLG in different solvents, as many factors (solute–solvent electrostatics, shape-specific interactions, different solvation of PBLG, etc.) contribute to the solute's orientation.

Conclusions

Although PBLG is a well-known chiral LC-forming polymer, its use as an orienting medium in organic structure determination is still not widespread. This is due to the fact that commercial PBLG orients most compounds too strongly, leading to serious problems in the interpretation of spectra. To gain a deeper insight into the factors modulating the induced degree of order and the resulting preferred orientation, we have started a systematic investigation into the LC phases of PBLG. In the first step, we synthesised PBLG covering a broad range of MW (axial ratios) and determined the critical concentrations for the phase transition LC to biphasic LC/isotropic as a function of the MW. The critical concentration shows asymptotical behaviour (decreasing steeply in the low-MW region), and reaches a final value (about 6 %) in the high-MW region. The quadrupolar splitting ($\Delta\nu_Q$), which can be used as a qualitative indicator for the degree of orientation, shows identical behaviour. With the high MW samples it is possible to improve spectral quality significantly.

In the next step, the alignment properties of IPC, which we chose as a model compound, in PBLG samples of different MW were investigated. The axial component of the orienting tensor (D_a), which is

Table 5. Comparison of the alignment properties of (+)-IPC in the LC phase of PBLG in different solvents.

PBLG	Solvent	(w/w)[a] [%]	IPC	$\|\Delta\nu_Q\|$[b] [Hz]	n(RDC)[c]	D_a[d] [10^{-4}]	R[e]	α[f]	β[f]	γ[f]	R^2[g]
4g	CDCl$_3$	7.1	(+)	208	11	5.1	0.53	110	101	136	0.999
4g	CD$_2$Cl$_2$	8.3	(+)	105	11	3.8	0.63	102	101	131	0.994
4g	C$_2$D$_2$Cl$_4$[h]	6.5	(+)	183	11	5.1	0.51	113	99	132	0.992
4g	[D$_8$]THF	12.4	(+)	75[i]	11	5.0	0.60	99	87	136	0.997
4g	[D$_7$]DMF	13.6	(+)	22[j]	8[k]	18.5	0.12	73	79	132	0.997

[a] Mass concentration of PBLG in the organic co-solvent. [b] Quadrupolar splitting of the solvent signal in the liquid crystal. [c] Number of $^1D_{CH}$ used for calculation of the parameters D_a, R, α, β, γ with PALES. [d] Axial component of the orienting tensor. [e] Rhombicity. [f] The three Euler angles relating the principle axis system and the initial molecular axis frame. Only one out of the four possible orientations is reported as the remaining three orientations can be constructed by symmetry operations. [g] Correlation factor for fit of calculated versus measured RDCs. [h] [D$_2$]-1,1,2,2-Tetrachloroethane. [i] Quadrupolar splitting of the O−CD$_2$ group. [j] Quadrupolar splitting of the D−C(=O)-deuterium. [k] Measurement was conducted at 315 K due to high viscosity (gel-like behaviour) of the LC phase.

a quantitative measure for the degree of orientation, decreased significantly for PBLG samples with higher MW. It was shown that the decrease in D_a is solely due to the higher achievable dilution of the LC phase and not an additional consequence of the increased flexibility of the polymer chain with increasing length. Furthermore, it was shown that the orientation of the solute is independent of the concentration of the LC phase and the MW of the polymer, which indicates that two different mechanisms are operative: one modulating the degree of order and one responsible for the orientation of the solute (with respect to the magnetic field).

Experimental Section

Gel permeation chromatography: Gel permeation chromatography (GPC) was performed in DMF+0.5% LiBr with a flow rate of 1.0 mL min⁻¹ at 70 °C on two 300×8 mm PSS GRAM 10 µm columns (100, 3000 Å) (Polymer Standard Service GmbH, Mainz, Germany). The detector employed was an RI ERC-7510 (Erma Inc.). The reported number-averaged MWs as well as the MWDs were determined against standard polystyrene samples from Polymer Standard Service GmbH, Mainz (Germany). The chromatograms were analysed using the software package WinGPC from Polymer Standard Service GmbH, Mainz (Germany).

NMR spectra: All spectra of IPC in isotropic and oriented samples were recorded on a 500 MHz spectrometer (Bruker DRX-500) with a triple resonance inverse probe equipped with a z-gradient. All measurements were carried out without sample spinning at 303 K unless otherwise stated. The total coupling constants (^1T) and scalar coupling constants (^1J) were measured by ω_2- and ω_1-coupled HSQC experiments by using an INEPT delay corresponding to 145 Hz. ω_2-coupled HSQCs were recorded without decoupling during acquisition by using the Echo/Antiecho selection scheme. A total of 8192 data points were sampled in the direct dimension over a spectral width of 10 ppm to give an FID resolution of 0.61 Hz. In the indirect dimension 256 data points were sufficient to prevent signal overlap. The spectra were processed with use of an exponential window function with 1 Hz line broadening in the direct dimension. In the indirect dimension a $\pi/2$-shifted sine-squared window function and zero filling by a factor of 4 was applied. ω_1-coupled HSQCs were recorded by removing the 180° proton pulse in the centre of the t_1 evolution period. A total of 1024 data points were sampled in the direct dimension over a spectral width of 10 ppm to give an FID resolution of 4.88 Hz. In the indirect dimension 2048 data points were sampled over a spectral width of 65 ppm to give an FID resolution of 3.99 Hz. The spectra were processed by using an exponential window function with 3 Hz line broadening and zero filling to 2048 data points in the direct dimension. In the indirect dimension a $\pi/2$-shifted sine-squared window function and zero filling by a factor of 2 was applied.

The dipolar coupling was calculated from the difference of the total coupling (anisotropic sample) and the scalar coupling (isotropic sample) by dividing by two, according to $^1T = {}^1J + 2 {}^1D$.[35] For the methyl groups, the measured $^1D_{CH}$ was converted to the corresponding $^1D_{CC}$ according to the literature.[54] Only the latter was used for the determination of the orienting tensor using PALES.[68] The module bestFit within PALES was used for determination of the orienting tensor properties and the Euler angles. The measured RDCs were scaled by a factor of -2 prior to calculation in order to gain the correct eigenvalues and Saupe order parameters (see Supporting Information), as PALES defines the dipolar coupling as $D = J - T$, whereas we chose to use a different definition, namely $T = J + 2D$ (leading to $D = (T - J)/2$).

NMR sample preparation: The LC phases were prepared directly in the NMR tube (5 mm o.d.). For high-MW polymers ≈50 mg or for low-MW polymers ≈80 mg of PBLG (with the MW corresponding to the letters

4a–h in Table 1 and Table 2) were weighed directly into the NMR tube, which contained a [D₆]DMSO capillary to provide the lock signal. For the NMR samples, which were prepared to examine the dependence of critical concentration and quadrupolar splitting on the molecular weight of PBLG, the organic co-solvent was added in small portions, the sample was centrifuged to achieve homogeneity, and ²H spectra were recorded. The critical concentration was determined (from the corresponding masses of PBLG and co-solvent) at the last concentration at which no signal of the isotropic solvent (which indicates the onset of the biphasic region) was observed.

For the NMR samples prepared to study the influence of the MW (and concentration) on the order of the solute, new samples were prepared by weighing the corresponding amount of PBLG **4b–f** into the sample tube (again ≈50 mg for high-MW and ≈80 mg for low-MW PBLGs). Afterwards, IPC (≈30 mg) and the organic co-solvent were added (for exact amounts see Supporting Information). The polymer was allowed to dissolve overnight and the sample centrifuged back and forth until the ²H signals were sharp and the line widths constant. When [D₇]DMF was used as solvent, the sample had to be heated to about 315 K, as below 310 K the sample behaved like a gel. All reported concentrations of the LC phases were calculated from the mass of the polymer weighed into the NMR tube and the mass of solvent necessary to provide the desired LC phase.

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