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Homo- and heteronuclear 2D NMR approaches to analyse a mixture of deuterated *unlike/like* stereoisomers using weakly ordering chiral liquid crystals

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Abstract

We describe several homo- and heteronuclear 2D NMR strategies dedicated to the analysis of anisotropic ^{2}H spectra of a mixture of dideuterated *unlike/like* stereoisomers with two remote stereogenic centers, using weakly orienting chiral liquid crystals. To this end, we propose various 2D correlation experiments, denoted "D(H)$_n$D" or "D(H)$_n$C" (with n = 1, 2), that involve two heteronuclear polarization transfers of INEPT-type with one or two proton relays. The analytical expressions of correlation signals for four pulse sequences reported here were calculated using the product-operators formalism for spin $I = 1$ and $S = 1/2$. The features and advantages of each scheme are presented and discussed. The efficiency of these 2D sequences is illustrated using various deuterated model molecules, dissolved in organic solutions of polypeptides made of poly-γ-benzyl-L-glutamate (PBLG) or poly-ε-carbobenzyloxy-L-lysine (PCBLL) and NMR numerical simulations.

Keywords: ^{2}H quadrupolar splittings; 2D experiments; Chiral liquid crystals; INEPT transfers; Proton relay; *u/l* Stereoisomers

1. Introduction

^{2}H NMR spectroscopy in chiral polypeptide liquid crystals provides original solutions to organic chemists for analyzing relative stereochemistry of molecules, determining enantiomeric purity of a mixture, or answering to specific analytical issues [1–4]. Among stereochemical problems met by chemists, the analysis of a mixture made of deuterated *unlike/like* (*u/l*) compounds with two remote stereogenic carbons of different stereochemistry for each asymmetric carbon is particularly challenging [5]. For illustration, typical molecules of interest are shown in Fig. 1. In these examples, the *unlike* and *like* isomers correspond to the achiral compound (*meso* form) and the enantiomers (*RR*/*SS*), respectively.

For such mixtures, the discrimination of diastereoisomeric forms (*u/l*) in isotropic NMR is not always possible, in particular when the stereogenic centers are far from each other [5]. Besides, the discrimination of enantiomers (*RR*/*SS*) is basically impossible since the NMR solvent is generally achiral. Alternatively, the use of ^{2}H–{^{1}H} or ^{13}C–{^{1}H} NMR spectroscopies in chiral liquid crystals can afford efficient solutions to separate the signals of three stereosiomers of mixtures, one achiral isomer (*meso*) and two enantiomers (*RR*/*SS*), on the basis of quadrupolar splitting or chemical shift anisotropy (CSA) differences [2]. Indeed, the oriented chiral solvent allows to orient differently in average the *u/l* diastereoisomers as well as enantiomers of the mixture.

For mixtures **1** or **2**, four distinct quadrupolar doublets are expected to be observed on ^{2}H–{^{1}H} spectra, assuming

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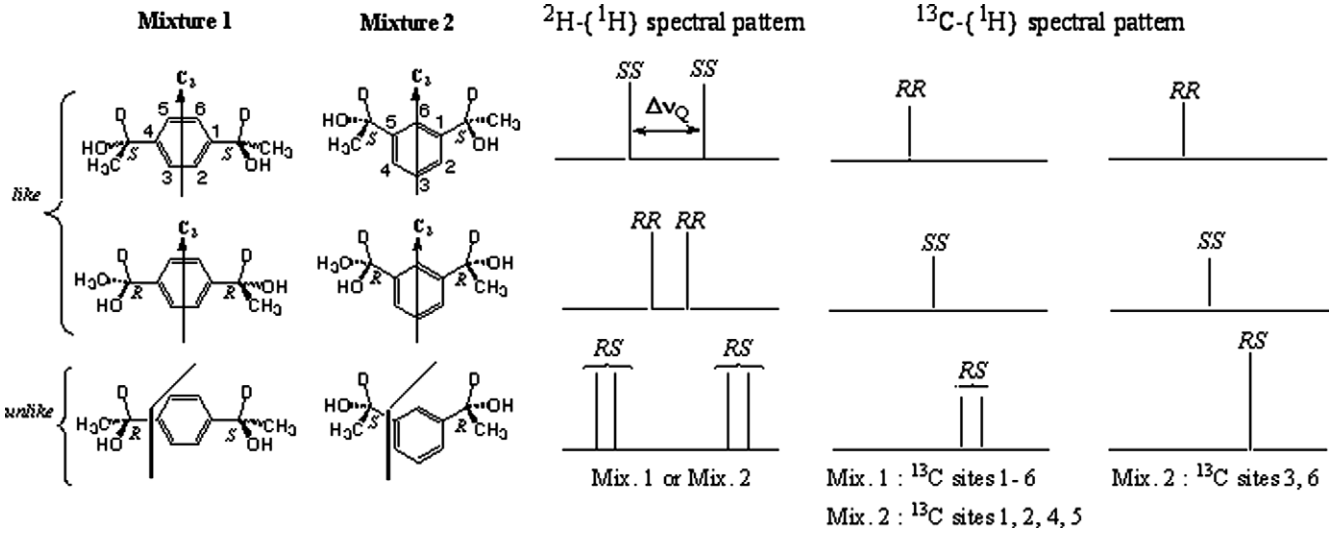

Fig. 1. Schematic ^{2}H–{^{1}H} and ^{13}C–{^{1}H} 1D spectral pattern expected to be observed for various isomers in mixtures **1** and **2** dissolved in a chiral mesophase when all compounds are spectrally discriminated. Due to the C_2 axis in the enantiomers, the two deuterons are homotopic, and so magnetically equivalent. The magnitude of $\Delta\nu_Q$s as well as the position of ^{13}C peaks are arbitrarily chosen. Due to weakness of the ^{2}H chemical shift anisotropy, all ^{2}H quadrupolar doublets are centred at the same chemical shift. The ^{13}C–{^{1}H} spectral patterns associated to asymmetric and methyl carbons (for mixtures **1** and **2**) are in principle identical to that expected for carbon sites 1–6 in mixture **1**. However, generally the ^{13}C chemical shift anisotropy for sp^3 hybridized carbons is much smaller than for aromatic sp^2 hybridized carbons, and hence only small spectral separations for the three isomers are expected for these sites.

that diastereoisomers and enantiomers are discriminated by the polypeptide liquid crystals and spectral separations are sufficiently large to prevent resonance overlaps, as schematically depicted in Fig. 1 [6]. Two of them originate from the discrimination of enantiotopic deuterons associated with the *meso* isomer ($RS = SR$) [7], the two others originating from the discrimination of enantiomers (*RR* and *SS*).

From the ^{13}C–{^{1}H} NMR point of view, the mixtures **1** and **2** must be considered separately. For mixture **1**, four ^{13}C resonances are expected to be observed for each non equivalent carbon site if the three stereoisomers are spectrally discriminated on the basis of ^{13}C chemical shift anisotropy differences (CSA) (see Fig. 1) [3]. This occurrence will be also encountered for mixture **2**, except for the ^{13}C sites labelled 3 and 6 for which only three distinct resonances are expected to be detected if all signals are well-resolved (see Fig. 1). Indeed, these carbon-13 sites belong to the symmetry plane in the *meso* molecule, and hence they cannot be differentiated.

From an analytical point of view, the spectral discrimination of stereoisomers based on $\Delta\nu_Q$s is generally more efficient than based on ^{13}C CSA [2,3]. Consequently, the central question arisen here is how to pair up and assign quadrupolar doublets belonging to *u*/*l* diastereoisomers, in particular when the enantiomeric and diastereosiomeric excesses are both equal to 0%. Indeed in this particular case, four quadrupolar doublets of identical intensity should be theoretically observed, and so their assignment is not straightforward.

The solution for solving this problem is not unique as we will see below, and various homo- and heteronuclear 2D NMR approaches will be presented in this methodological article, along with their evaluation on test molecules. As seen from the calculated transfer efficiency, the most appropriate strategies will mainly depend on the structure of the molecules under investigation and of their orientation. The actual possibility to generate heteronuclear polarization transfers to separate the useful NMR information proved heavily system-dependent. The initial goal could not be fully reached on mixtures **1** and **2**, but the steady development of new or improved chiral liquid crystals could help solving this issue.

2. Results and discussion

2.1. Overview of possible 2D NMR strategies

Considering the structure of molecules involved in mixtures **1** and **2**, several possible 2D NMR strategies can be proposed to facilitate the assignment of the quadrupolar doublets for *meso* and enantiomeric compounds, and subsequently to measure their diastereoisomeric excess when knowing the major diastereoisomer.

The general principle of these ^{2}H assignment strategies is based on the fact that only the *meso* compound possesses two deuterons that can be potentially correlated. Three possibilities can be proposed: (i) the use of ^{2}H–^{2}H correlations through direct dipolar couplings (see Fig. 2a), (ii) the ^{2}H–^{2}H correlations *via* multiple polarization transfers involving heteronuclear atoms (^{1}H or ^{13}C) as relays (see Fig. 2b–f), (iii) the use of ^{2}H–^{13}C correlations if a specific spectral property exists, that can be exploited in ^{13}C NMR (see Fig. 2g and h).

The simplest approach is based on the correlation of quadrupolar doublets through the existence of ^{2}H–^{2}H total coupling in the various isomers. This strategy using ^{2}H–^{2}H

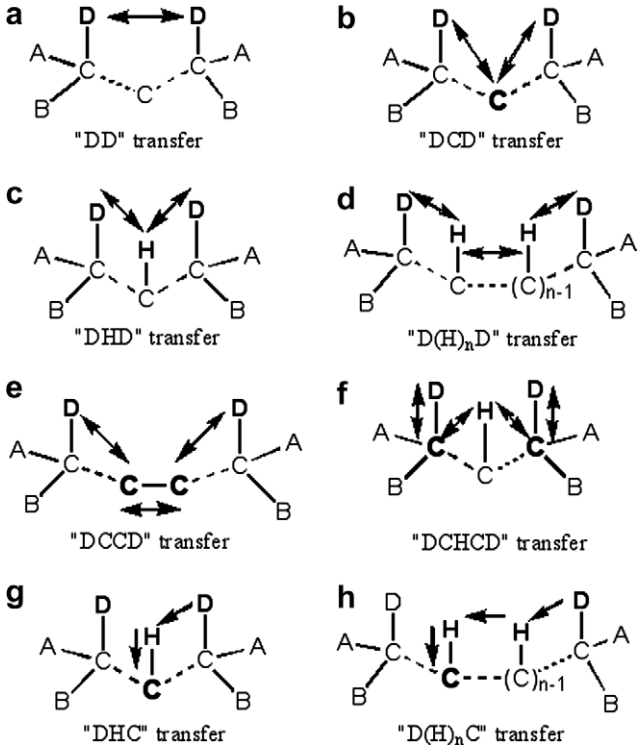

Fig. 2. Examples of (a–f) homo- and (g and h) heteronuclear NMR strategies to analyse the mixtures **1** and **2**, and involving none, two or four heteronuclear atom(s) as relays.

COSY 2D experiments was successfully applied to analyse and assess diastereoisomeric and enantiomeric purity in an *u/l* mixture where stereoisomers possessed a "CD_2" group [8,9]. Unfortunately for remote deuterons (as in the case of mixtures **1** and **2**), the scalar coupling is null while the magnitude of ^2H–^2H dipolar coupling is predicted to be too small when weakly orienting liquid crystals, as organic solutions of polypeptides, is used. Chiral cholesteric thermotropic mesophases could be suggested to increase the solute ordering and so produce larger dipolar couplings. However the existing mesophases show generally small enantioselectivities and are rather bad organic solvents [10]. Other homonuclear strategies involving either ^2H–^{13}C or ^2H–^1H heteronuclear polarization transfers can be proposed, as shown in Fig. 2. Thus strategies b, c and f can be proposed to analyze mixture **2** while strategies d and e are more adapted to analyze mixture **1**. Note however that strategies e and f are very difficult to apply in the case of non-^{13}C-enriched compounds due the low probability to find isotopomers with two ^{13}C nuclei. Finally, in the case of mixture **2**, heteronuclear strategies, g and h, involving one or two proton relays can be valuable to correlate the deuterons to carbon site 6 (eventually site 3) that belongs to the plane of molecular symmetry.

2.2. The "DCD" correlation experiments

Recently, we have described the DECADENCY 2D experiments to correlate the ^2H signals of two geminal deuterons in prochiral molecules [11]. Two kinds of polarization transfer using either DEPT- or INEPT-type schemes were explored [12,13]. In Fig. 3a is shown the DECADENCY-INEPT 2D sequence.

After a four-step phase cycle and disregarding all relaxation terms and phase factors, the expression of correlation peaks (CPs) is

$$S_{CP}(t_1,t_2) \propto \tfrac{2}{3}i \times \left\{ \sin\left[2\pi\nu_{D^{i,j}}(t_1+\tau)\right] \times \cos\left[\pi\Delta\nu_{Q^{i,j}}(t_1+\tau)\right] \right\} \times f_{corr}(\tau,\tau') \times \left\{ \begin{array}{l} e^{i\left[2\pi\nu_{D^{i,j}}(\tau+t_2)-\pi\Delta\nu_{Q^{i,j}}(\tau+t_2)\right]} \\ +e^{i\left[2\pi\nu_{D^{i,j}}(\tau+t_2)+\pi\Delta\nu_{Q^{i,j}}(\tau+t_2)\right]} \end{array} \right\} \quad (1)$$

where $f_{corr}(\tau,\tau')$ is the transfer function governing the amplitude of correlation peaks on the 2D map [14]. For the "DCD" pulse sequence, $f_{corr}(\tau,\tau')$ is:

$$f_{corr}(\tau,\tau') = \left\{ \begin{array}{l} \sin\left[\pi T_{CD^{i,j}}(\tau)\right] \times \sin\left[2\pi T_{CD^{i,j}}(\tau')\right] \\ \times \sin\left[2\pi T_{CD^{i,j}}(\tau')\right] \times \sin\left[\pi T_{CD^{i,i}}(\tau)\right] \end{array} \right\} \quad (2)$$

In these equations, $\nu_{D^{i,j}}$ and $\Delta\nu_{Q^{i,j}}$ are the frequency offsets and quadrupolar splittings of i and j deuterons, respectively, while $T_{CD^{i,j}}$ is the ^{13}C–^2H total coupling ($T_{CD} = J_{CD} + 2D_{CD}$). Note that Eqs. (1) and (2) were calculated with the help of product-operators formalism for spin $I = 1$ and $S = 1/2$ that was proposed recently [11]. In all homonuclear ^2H–^2H correlation experiments, diagonal peaks (DPs) and autocorrelation peaks (APs) are also present in the 2D map (for illustration, see Fig. 4a) but only the equations of CPs, that contain the useful information, will be given in this work.

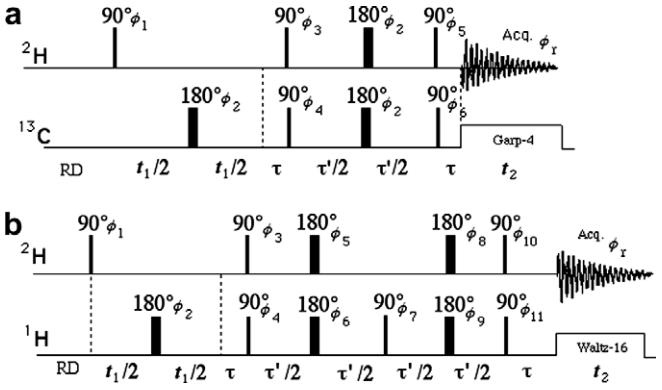

Fig. 3. (a) Pulse scheme of the DECADENCY-INEPT 2D sequence. The basic four-step phase cycling is: $\phi_1 = 2(x)$, $2(-x)$; $\phi_2 = \phi_3 = \phi_5 = \phi_6 = 4(x)$; $\phi_4 = 2(x,-x)$; $\phi_r = x,-x,-x,x$. GARP-4 sequence suppresses ^{13}C–D couplings during the acquisition period. When required, the ^1H nuclei are decoupled by applying the WALTZ-16 pulse scheme over the sequence. (b) Pulse scheme of the "DHHD" 2D sequence. The basic four-step phase cycling is: $\phi_1 = 2(x)$, $2(-x)$; ϕ_2, ϕ_3, ϕ_5 to $\phi_{11} = 4(x)$; $\phi_4 = 2(x,-x)$; $\phi_r = x, -x, -x, x$. To compensate pulse imperfections, the phase cycling can be expanded to eight steps where $\phi_{10} = 4(x)$, $4(-x)$ and $\phi_r = x, -x, -x, x, -x, x, x, -x$, while for other pulses, the four-step phase cycling is repeated twice.

Eq. (2) shows that the intensity of CPs (I_{CP}) varies with delay τ and τ'. In the ideal case, where $|T_{CD^i}| = |T_{CD^j}| = |T_{CD}|$, and disregarding relaxation effects, I_{CP} is maximized when $\tau = 1/2(|T_{CD}|)$ and $\tau' = 1/(4|T_{CD}|)$ [11]. Actually, the ideal case where $|T_{CD^1}| = |T_{CD^2}|$ (for a "D^1–C–D^2" system) does not exist, but generally a good compromise is obtained by averaging the T_{CD} values.

This sequence was successfully tested in the case of geminal deuteriums to analyse the anisotropic ^{2}H–{^{1}H} spectrum of a mixture of two deuterated prochiral compounds [11]. Assuming that the $^3T_{CD}$ coupling is not null, such an approach seems rather well-adapted for analyzing mixture **2**, because here the carbon atom labelled 6 (see Fig. 1) could play the same role as the ^{13}C atom in the CD_2 group. Unfortunately, no three-bond C–D total coupling was observed in the various deuterated isomers of mixtures **2**, mainly due to the long distance between ^{13}C and ^{2}H sites and the weak alignment of solutes in polypeptide mesophases.

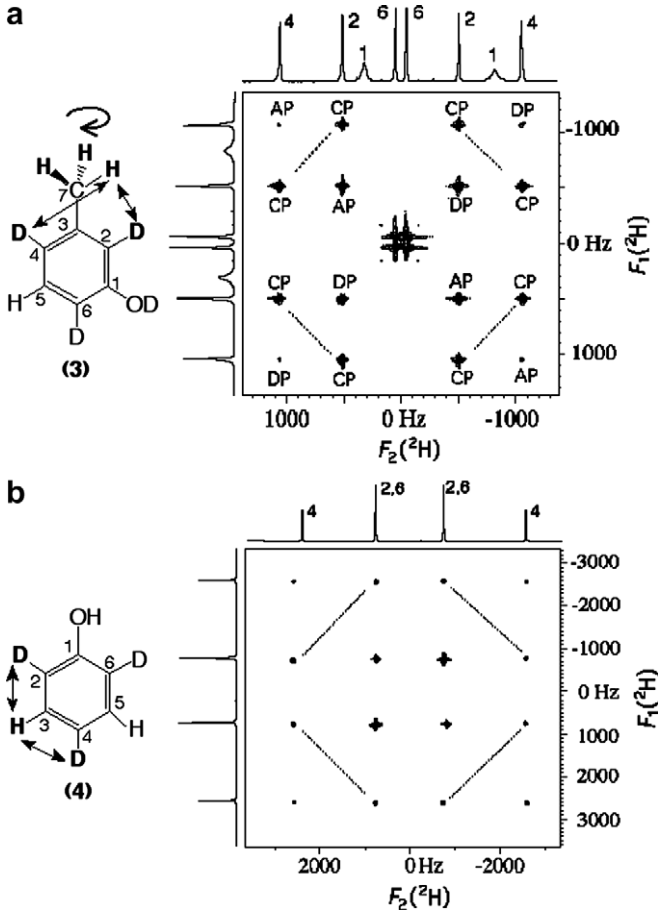

Fig. 4. Experimental 92.1 MHz "DHD" 2D spectra of **3** (a) and **4** (b) dissolved in PBLG/$CHCl_3$ phase at 300 K. The 2D matrix is 256 (t_1) × 1538 (t_2) data points, with NS = 32 (a) and 512 (t_1) × 2048 (t_2) data points, with NS = 8 (b). Exponential filtering (1 Hz) in F_2 and F_1 dimensions is applied in both experiments. On the 2D map (a), the diagonal peaks (DP), autocorrelation peaks (AP) and cross-correlation peaks (CP) associated with the D^2 and D^4 deuteriums are labelled.

2.3. The "DHD" correlation experiments

An alternative to the "DCD" experiment consists in using experiments with a "DHD"-type transfer where the carbon relay is replaced by a proton relay. In this new scheme, the ^{2}H magnetization is transfered *via* an highly abundant nucleus (99.985%) thus increasing the intrinsic sensitivity of the experiment. In addition, we benefit from a nucleus with a magnetogyric ratio four times larger than the one of carbon. Hence, in the particular case of mixture **2**, we can *a priori* expect larger dipolar couplings between deuterons and H^6 than between deuterons and C^6.

The "DHD" pulse sequence is identical to the DECADENCY-INEPT scheme but the proton nucleus plays the role of the ^{13}C nucleus. Nevertheless, from the polarization transfer point of view, the situation can be more complex than for "DCD" transfers as proton(s) relaying the single quantum coherences (SQC's) can be also coupled with other surrounding protons in the molecule. This occurrence does not exist for the "DCD" transfers due to the low abundance of isotopomers with two ^{13}C nuclei.

After a four-step phase cycle and disregarding all relaxation terms, the expression of CPs for the "DHD" sequence is formally identical to Eq. (1), but the transfer function can differ according to the ^{1}H–^{1}H coupling patterns. For a spin system "D^i–$H^k_n(H^l)$–D^j" where the $D^{i,j}$ are coupled to n equivalent protons, H^k, weakly coupled themselves to several protons, H^l (equivalent or not), f_{corr} is equal to:

$$f_{corr}(\tau,\tau') = n^2 \times \left\{ \begin{array}{l} \sin\left[\pi T_{D^iH^k}\tau\right]\cos^{n-1}\left[\pi T_{D^iH^k}\tau\right] \\ \times \sin\left[2\pi T_{D^iH^k}\tau'\right]\sin\left[2\pi T_{D^iH^k}\tau'\right] \\ \times \cos^{n-1}\left[3\pi D_{H^kH^k}\tau'\right]\left\{\prod_l \cos\left[\pi T_{H^kH^l}\tau'\right]\right\} \\ \times \sin\left[\pi T_{D^iH^k}\tau\right]\cos^{n-1}\left[\pi T_{D^iH^k}\tau\right] \end{array} \right\} \quad (3)$$

The choice of the τ delay for maximizing f_{corr} depends both on the T_{DH} values and the number (n) of protons which contribute to the relay. In the ideal case where $|T_{D^iH}| = |T_{D^jH}| = |T_{DH}|$, the maximum transfer during τ delay occurs when $\tau = 1/|2T_{DH}|$, $1/|4T_{DH}|$ and $0.196/|T_{DH}|$ for a methyne, methylene (if proton are equivalent), and a methyle group, respectively [15]. The choice of τ' is less trivial due to its dependency on the magnitude of (i) ^{2}H–^{1}H total couplings, (ii) ^{1}H–^{1}H total couplings if the proton(s) participating to the relay is (are) also coupled with other inequivalent protons, (iii) the ^{1}H–^{1}H dipolar coupling between the n equivalent protons involved in the relay. In the simple, ideal case where $|T_{D^iH}| = |T_{D^jH}| = |T_{DH}|$ and $|D_{H^kH^k}| = |T_{H^kH^l}| = 0$, then we have $\tau' = 1/|4T_{DH}|$. As for the "DCD" experiments, the average of $|T_{DH}|$ (provides a suitable value for experimentally optimizing the polarization transfers.

Although the relaxation terms were not shown in Eq. (3), the efficiency of f_{corr} is not independent of T_2 relaxation effect [14]. Thus in the general case, we can show that

$f_{corr}(\tau,\tau')$ depends on the exponential term $\exp(-\tau/T_2^{D^i})\exp(-\tau'/T_2^{H^k})\exp(-\tau/T_2^{D^j})$. *A priori*, the choice of τ and τ' depends on the T_2 times of deuterons and protons, respectively. In practice, as $T_2^D \approx |1/T_{DH}|$, the τ delay must be shortened compared to the ideal value in order to minimize the losses due to the T_2 relaxation. In contrast, as generally $T_2^H \geqslant |1/T_{DH}|$, the optimal τ' value can be chosen independently of the $T_2{}^H$ value.

To experimentally test this sequence, we chose two model molecules, the 2,4,6-trideuterated-3-methylphenol (**3**) and 2,4,6-trideuterated-phenol (**4**) dissolved in mesophases made of poly-γ-benzyl-L-glutamate (PBLG) and $CHCl_3$ or poly-ε-carbobenzyloxy-L-lysine (PCBLL) and $CHCl_3$ (see Table 1). These aligned solutes (see Fig. 4) are interesting theoretical and experimental models for various reasons. First, the couplings between deuterons are null or too small and cannot generate direct correlations that could be erroneously interpreted as correlations due to the "DHD" transfer. Second, the heteronuclear ^2H–^1H total couplings over four bonds are null in **3** and **4**, thus limiting the number of terms in f_{corr}. Third, these solutes allow testing the "DHD" transfer *via* different proton spin systems. Thus for compound **3**, the "DHD" transfer can be performed through either a single proton, H^5 (coupled or not to methyl group protons, H^7) or the three equivalent protons of methyl group (coupled or not to proton H^5). For **4**, we can consider a "DHD" transfer using a single proton, that can be a priori involved either in an A_2 or AA′ spin system. These differences in proton spin systems affect the expression of the transfer function, $f_{corr}(\tau,\tau')$.

For **3**, and assuming that $^5T_{H^5H^7}$ is null, the transfer function between D^4 and D^6 is similar to Eq. (3), except that carbon subscripts are replaced by the proton subscripts. In contrast, if H^5 and H^7 are weakly coupled, we are in presence of an AX_3 proton spin system, and a new term depending on the $^5T_{H^5H^7}$ coupling appears in $f_{corr}(\tau,\tau')$:

$$f_{corr}(\tau,\tau') = \left\{ \begin{array}{l} \sin[\pi^3 T_{D^{4,6}H^5}\tau] \\ \times \sin[2\pi^3 T_{D^{4,6}H^5}\tau'] \sin[2\pi^3 T_{D^{4,6}H^5}\tau'] \\ \times \cos^3[\pi^5 T_{H^5H^7}\tau'] \\ \times \sin[\pi^3 T_{D^{4,6}H^5}\tau] \end{array} \right\} \quad (4)$$

Experimentally, the nuclei D^4 and H^5 are not coupled to each other, thus preventing the possibility to correlate D^4 to D^6 through H^5.

In compound **3**, a second type of transfer is possible through the three equivalent protons of methyl group, H^7. Assuming that the total coupling $^5T_{H^5H^7}$ is not null, the transfer function between D^2 and D^4 is now governed by the following equation:

$$f_{corr}(\tau,\tau') = 9 \times \left\{ \begin{array}{l} \sin[\pi^4 T_{D^{2,4}H^7}\tau]\cos^2[\pi^4 T_{D^{2,4}H^7}\tau'] \\ \times \sin[2\pi^4 T_{D^{2,4}H^7}\tau']\sin[2\pi^4 T_{D^{4,2}H^7}\tau'] \\ \times \cos^2[3\pi^2 D_{H^7H^7}\tau']\cos[\pi^5 T_{H^5H^7}\tau'] \\ \times \sin[\pi^4 T_{D^{4,2}H^7}\tau]\cos^2[\pi^4 T_{D^{4,2}H^7}\tau] \end{array} \right\} \quad (5)$$

Note that the $\cos[\pi^5 T_{H^5H^7}\tau']$ term becomes equal to 1 when $^5T_{H^5H^7} = 0$.

Fig. 4a shows the "DHD" 2D map of **3** when the polarization transfer involves protons of the methyl group. We have experimentally observed the existence of homonuclear coupling between methyl protons and H^5, and hence $f_{corr}(\tau,\tau')$ is given by Eq. (5). The ideal values for τ should correspond to $0.196/|^4T_{DH}|$, assuming that the $|^4T_{D^2H^7}| = |^4T_{D^4H^7}| = |^4T_{DH}|$. In practice, the optimal value of τ is found to be equal to 19.8 ms, thus corresponding to a good balance between the defocusing under the T_{HD} couplings (≈8.5 Hz) and the T_2 relaxation times for D^6 and D^4(≈57 ms). On the other hand, the τ' optimal value ($\tau' = 35.4$ ms) is determined by taking into account the H^5–H^7 total coupling (7 Hz) and the H^7–H^7 dipolar coupling (8 Hz). As expected on the 2D map, CPs arise only between D^2 and D^4 (see Fig. 4a) while the DPs and APs are observed for all deuterons, including also D^6 due to the coupling between D^6 and H^5. The difference of intensity in DPs and APs for D^2 and D^4 results from the choice of both τ and τ' values [11].

As compound **4** has a C_{2v} symmetry, the H^3 and H^5 protons belong either to an AA′ or to an A_2 spin system depending if H^3 and H^5 are coupled or not. Due to the second order nature of an AA′ spin system, the analytical expression of $f_{corr}(\tau,\tau')$ is very complex to calculate, and was not established. Experimentally, the analysis of both ^1H–{^2H} and ^2H–{^1H} spectra indicates that the proton

Table 1
Labelling and composition of the liquid–crystalline samples used in the present work

Solute	Solute (mg)	PBLG[a] (mg)	PCBLL[b] (mg)	$CHCl_3$ (mg)	% of polymer (wt)
1	17	130	0	413	23.2
2	21	0	100	451	17.5
3	11	101	0	404	19.5
3	12	0	99	470	17.0
4	10	100	0	424	18.8
5[c]	75	101	0	454	15.9

[a] The DP of PBLG is 782.
[b] The DP of PCBLL is 778.
[c] The ee is over 95%.

is an A_2 spin system with no ^1H–^1H dipolar coupling. Hence, in this case, $f_{corr}(\tau,\tau')$ is equal to:

$$f_{corr}(\tau,\tau') = 2 \times \left\{ \begin{array}{l} \sin\,[\pi^3 T_{D^4H^{3,5}}\tau]\,\cos\,[\pi^3 T_{D^4H^{3,5}}\tau] \\ \times \sin\,[2\pi^3 T_{D^4H^{3,5}}\tau']\,\sin\,[2\pi^3 T_{D^{2,6}H^{3,5}}\tau'] \\ \times \sin\,[\pi^3 T_{D^{2,6}H^{3,5}}\tau] \end{array} \right\} \quad (6)$$

Fig. 4b shows the "DHD" 2D map of **4** where the correlations between $D^2(D^6)$ and D^4 were successfully observed. In this second example, the optimal values of τ and τ' were found to be equal to 15.2 and 17.4 ms. As previously, the difference of intensity in DPs and APs results from the choice of τ and τ' values.

2.4. The "DHHD" correlation experiments

The "DHHD" 2D sequence is a variation of the "DHD" 2D pulse sequence in which a 90° pulse is introduced in the middle of the τ' period in order to relay the ^1H magnetization between neighbor protons. The sequence is depicted in Fig. 3b. During the τ' delays, the ^1H SQCs evolve under the effect of couplings $|T_{DH}|$ and $|T_{HH}|$. Thus during the two first $\tau'/2$ delays, the ^1H magnetization, antiphase with respect to ^1H–^2H coupling, is converted into ^1H magnetization, antiphase with respect to ^1H–^1H coupling. During the two last $\tau'/2$ delays, the previous mechanism is reversed. The two pairs of simultaneous ^1H and ^2H 180° pulses implemented in the sequence remove the ^1H chemical shifts without affecting the homo- and heteronuclear couplings.

After a four-step phase cycle, the analytical expression of CP signals is formally identical to Eq. (1) but $f_{corr}(\tau,\tau')$ differs from that obtained in the "DHD" transfer. Thus, in the case of a spin system of the form "D^i–H^k_m–H^l_n–D^j" where H^k_m and H^l_n are weakly coupled, $f_{corr}(\tau,\tau')$ is equal to:

$$f_{corr}(\tau,\tau') = (n \times m)^2 \times \left\{ \begin{array}{l} \sin\,[\pi T_{D^iH^k}\tau]\,\cos^{\,m-1}[\pi T_{D^iH^k}\tau] \\ \times \sin\,[2\pi T_{D^iH^k}\tau']\,\cos^{\,m-1}[3\pi D_{H^kH^k}\tau'] \\ \times \sin\,[\pi T_{H^kH^l}\tau']\,\cos^{n-1}\,[\pi T_{H^kH^l}\tau'] \\ \times \sin\,[2\pi T_{D^jH^l}\tau']\,\cos^{n-1}\,[3\pi D_{H^lH^l}\tau'] \\ \times \sin\,[\pi T_{H^kH^l}\tau']\,\cos^{m-1}\,[\pi T_{H^kH^l}\tau'] \\ \times \sin\,[\pi T_{D^jH^l}\tau]\,\cos^{n-1}\,[\pi T_{D^jH^l}\tau] \end{array} \right\} \quad (7)$$

In Eq. (7), the relaxation terms have been disregarded, but in the general case, we can show that $f_{corr}(\tau,\tau')$ is weighted by a $\exp(-\tau/T_2^{D^i})\exp(-\tau'/T_2^{H^k})\exp(-\tau'/T_2^{H^l})\exp(-\tau/T_2^{D^j})$ factor. Here again, the optimal τ delay is dependent on the T_2^D values, and thus will be generally shortened compared to the ideal value to minimize losses due to T_2 relaxation.

For illustration, compound **3** can be used as an interesting example since the coupling between H^7 and H^5 is not null (see above). Under this condition, it is possible to generate a correlation between deuterons D^2 and D^6 through H^7 and H^5. However in this case, an additional term of the form, $[1+2\cos(2\pi^4 T_{D^4H^7}\tau')]/3$ must be included in f_{corr}, since the ^1H SQCs of the methyl group also evolve under the effect of the coupling with D^4 (see above).

Using deuterium and proton notations associated with compound **3**, $f_{corr}(\tau,\tau')$ becomes:

$$f_{corr}(\tau,\tau') = 9 \times \left\{ \begin{array}{l} \sin\,[\pi^4 T_{D^2H^7}\tau]\,\cos^2\,[\pi^4 T_{D^2H^7}\tau] \\ \times \sin\,[2\pi^4 T_{D^2H^7}\tau'][1+2\cos(2\pi^4 T_{D^4H^7})\tau']/3 \\ \times \sin\,[\pi^5 T_{H^5H^7}\tau']\,\cos^2\,[3\pi^2 D_{H^7H^7}\tau'] \\ \times \sin\,[2\pi^3 T_{D^6H^5}\tau']\,\sin\,[\pi^5 T_{H^5H^7}\tau']\cos^2\,[\pi^5 T_{H^5H^7}\tau'] \\ \times \sin\,[\pi^3 T_{D^6H^5}\tau] \end{array} \right\} \quad (8)$$

Fig. 5 shows the "DHHD" 2D map of **3** where the homonuclear correlations between D^2 and D^6 were successfully observed. In this second example, the optimal τ value is equal to 18.5 ms, and results from a compromise between the theoretical ideal value and the short T_2 values for deuterons (≈57 ms). From Eq. (8), the optimal τ' value is 81.8 ms.

Similarly to the "DHD" 2D map shown in Fig. 4a, we might expect to see the DPs and APs associated with the passive deuteron, D^4, as well as CPs between D^4 and D^6, but the choice of τ and τ' values leads to no visible peaks (even at very low level). Finally it could be noted that the central 90° pulse used for relaying proton magnetization can be replaced by a MLEV-type sequence flanked with two trim pulses that should be a reliable method to transfer ^1H polarization through more than two protons [16,17].

2.5. The "DHC" and "DHHC" correlation experiments

The "DHC" or "DHHC" correlation 2D experiments can be very efficient to analyse the case of mixture **2**. Indeed, as described above, the carbon atoms, noted 6 and 3, for *meso* compound in mixture **2** belong to the plane of symmetry, and so cannot show two separate resonances contrarily to the 1/5 and 2/4 carbon atom pairs. Conse-

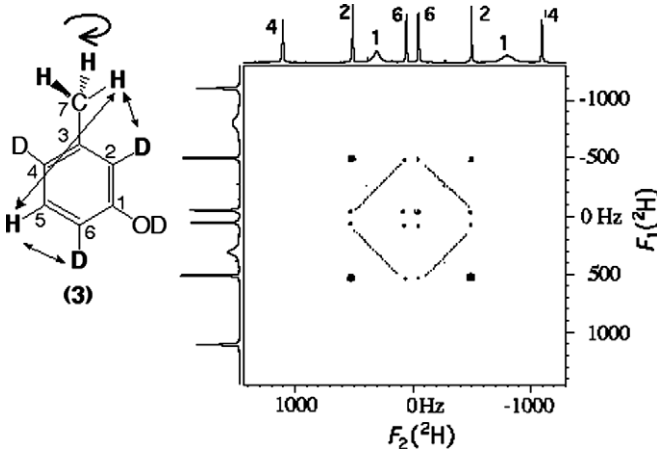

Fig. 5. Experimental 92.1 MHz "DHHD" 2D spectra of **3** in PBLG/$CHCl_3$ phase at 300 K. The 2D matrix is 256 (t_1) × 1538 (t_2) data points, with NS = 288. Exponential filtering (3 Hz) in F_2 and F_1 dimensions is used. The 2D map is symmetrised.

quently, taking advantage of this particular spectral feature associated with the molecules of mixture **2**, we should be able to assign the diastereoisomeric ^{2}H doublets from ^{2}H/^{13}C correlations.

The "DHC" pulse 2D sequence proposed here is shown in Fig. 6a and b. For such an experiment, the DPs and APs do not exist, thus strongly reducing the number of peaks in the 2D map.

Whereas the beginning of the sequence is similar to the "DHD" 2D experiment, the second heteronuclear INEPT transfer converts the ^{1}H SQCs into an observable ^{13}C magnetization during acquisition. The combination of three 180° pulses implemented as shown in Fig. 6 (top and middle) allows the evolution of ^{1}H SQCs under the effect of ^{1}H–^{2}H and ^{1}H–^{13}C couplings with elimination of the ^{1}H chemical shift evolution when $\tau_1 = \tau_2 + \tau_3$ [18]. In practice, the position of ^{2}H and ^{13}C 180° pulses depends on the magnitude of $|2T_{DH}|$ and $|T_{CH}|$. Fig. 6a and b present the "DHC" sequence that must be used when $|2T_{DH}| < |T_{CH}|$ and $|2T_{DH}| > |T_{CH}|$, respectively. As seen, the triggering order of ^{13}C and ^{2}H 180° pulses in both sequences is simply reversed. Finally, if the proton (or group of equivalent protons) used as relay is also coupled with other protons, then the ^{1}H magnetization evolves also under the effect of coupling, $|T_{HH}|$ during $\tau_1 + \tau_2 + \tau_3$.

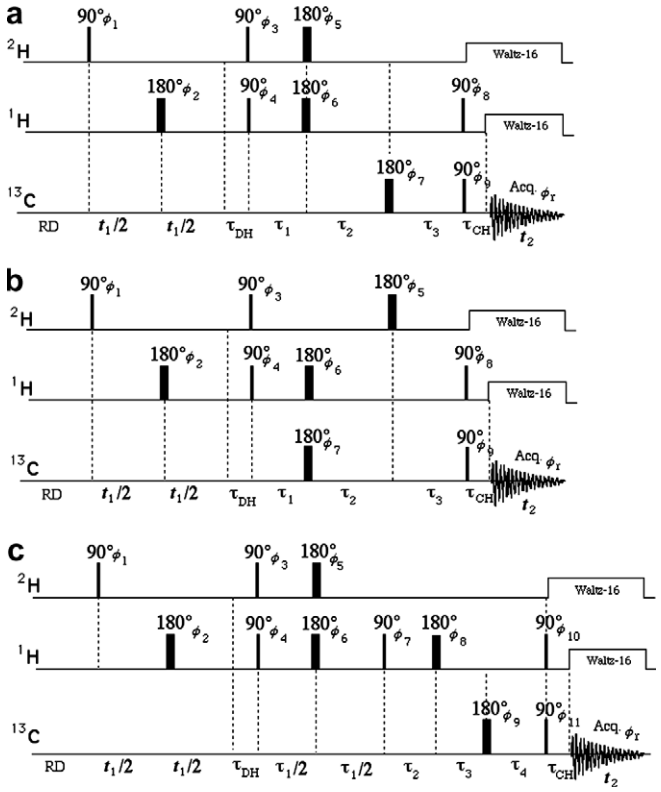

Fig. 6. Pulse scheme of the (a and b) "DHC" and (c) "DHHC" sequences using two INEPT-type transfers. Sequence a (b) is applied when $|2T_{DH}| < |T_{CH}|$ ($|2T_{DH}| > |T_{CH}|$). The basic two-step phase cycling is: (a and b) $\phi_1 = x, -x$; ϕ_2 to $\phi_9 = x, x$; $\phi_r = x, -x$; and (c) $\phi_1 = x, -x$; ϕ_2 to $\phi_{11} = x, x$; $\phi_r = x, -x$.

After a two-step phase cycle and disregarding the relaxation term, the general form of expression of the NMR signal for an "DHC" 2D experiment is given by:

$$S(t_1,t_2) \propto \left\{ \begin{array}{l} \cos[(2\pi\nu_D + \pi\Delta\nu_Q)(t_1+\tau_{DH})] \\ +\cos[(2\pi\nu_D - \pi\Delta\nu_Q)(t_1+\tau_{DH})] \end{array} \right\} \times f_{corr}(\tau_{DH},\tau_1,\tau_2,\tau_3,\tau_{CH}) \times \{e^{i[2\pi\nu_C(\tau_{CH}+t_2)]}\} \quad (9)$$

As previously, $f_{corr}(\tau_{DH}, \tau_1, \tau_2, \tau_3, \tau_{CH})$ is the transfer function. For simplifying notations, we will denote hereafter $f_{corr}(\tau_{DH}, \tau_1, \tau_2, \tau_3, \tau_{CH})$ as $f_{corr}(\tau_p)$. For a "D^i–H^k_n(H^l)–C^j" spin system where H^k and H^l protons are weakly coupled, its analytical expression is:

$$f_{corr}(\tau_p) = n^2 \times \left\{ \begin{array}{l} \sin[\pi\ T_{D^iH^k}\tau_{DH}]\cos^{n-1}[\pi T_{D^iH^k}\tau_{DH}] \\ \times \sin[2\pi\ T_{D^iH^k}(\tau_1 \pm \tau_2 + \tau_3)] \\ \times \sin[\pi\ T_{C^jH^k}(\tau_1 \mp \tau_2 + \tau_3)] \\ \times \cos^{n-1}[3\pi\ D_{H^kH^k}(\tau_1+\tau_2+\tau_3)] \\ \times \prod_l \cos[\pi\ T_{H^kH^l}(\tau_1+\tau_2+\tau_3)] \\ \times \sin[\pi\ T_{C^jH^k}\tau_{C^jH^k}]\cos^{n-1}[\pi T_{C^jH^k}\tau_{C^jH^k}] \end{array} \right\} \quad (10)$$

when setting $\tau_1 = \tau_2 + \tau_3$. As seen in Eq. (10) (lines 2 and 3), the effective evolution periods due to couplings T_{DH} and T_{CH} are equal to $(\tau_1 + \tau_2 + \tau_3)$ and $(\tau_1 - \tau_2 + \tau_3)$, for the first sequence, and $(\tau_1 - \tau_2 + \tau_3)$ and $(\tau_1 + \tau_2 + \tau_3)$ for the second one.

Assuming no ^{1}H–^{1}H couplings, then $f_{corr}(\tau_p)$ of the first "DHC" sequence is ideally maximized when $\tau_{DH} = 1/|2T_{DH}|$, $\tau_1 = 1/|8T_{DH}|$, $\tau_2 = 1/|8T_{DH}| - 1/|4\ T_{CH}|$ if $|2T_{DH}| < |T_{CH}|$, $\tau_3 = 1/4T_{CH}$ and $\tau_{CH} = 1/|2T_{CH}|$. For the second "DHC" sequence, $\tau_1 = 1/|4T_{CH}|$, $\tau_2 = 1/|4T_{CH}| - 1/|8T_{DH}|$ and $\tau_3 = 1/|8T_{DH}|$. From a relaxation point of view, $f_{corr}(\tau_p)$ depends on the following term $\exp(-\tau_{DH}/T_2^{D^i})\ \exp(-(\tau_1+\tau_2+\tau_3)/T_2^{H^k})\ \exp(-\tau_{CH}/T_2^{C^j})$ in both sequences. Comparing the $1/T_{ij}$ values to the ^{1}H, ^{2}H and ^{13}C T_2 relaxation values, it is clear that only the choice of τ_{DH} can be affected by the T_2 relaxation.

To illustrate the efficiency of the "DHC" sequence in oriented media, we have analysed the case of compounds **5** and **3**. For **5**, the "DHC" transfer involves a single proton as relay while for **3**, the transfer implicates three equivalent protons that are dipolar coupled. For solute **5**, the condition $|2T_{DH}|$ (=10 Hz) $< |T_{CH}|$ (=208 Hz) is experimentally fulfilled, and so the first "DHC" pulse sequence (Fig. 6a) must be applied. Assuming that D^1 is only coupled with proton H^8, itself weakly coupled to H^7, the expression of $f_{corr}(\tau_p)$ is:

$$f_{corr}(\tau_p) = \left\{ \begin{array}{l} \sin[\pi^4 T_{D^1H^8}\tau_{DH}] \\ \times \sin[2\pi^4 T_{D^1H^8}(\tau_1+\tau_2+\tau_3)] \\ \times \sin[\pi^1 T_{C^8H^8}(\tau_1-\tau_2+\tau_3)] \\ \times \cos[\pi^3 T_{H^7H^8}(\tau_1+\tau_2+\tau_3)] \\ \times \sin[\pi^1 T_{C^8H^8}\tau_{CH}] \end{array} \right\} \quad (11)$$

Fig. 7a reports the "DHC" 2D map obtained for **5** when the refocusing delays of the "DHC" sequence are optimized for correlating deuteron D^1 to carbon C^8. No further correlation is observed on the 2D map, mainly since the couplings between D^1 and the axial and equatorial protons, H^2, of cyclohexenyl ring are null. In this example, it is interesting to emphasize that the assignment of the ^{13}C peaks around 128.5 ppm is not trivial using, the additivity rules of substituents for instance, and contradictory assignments for carbon atoms, C^5 and C^8, can be found using NMR data bases or prediction softwares such as ACD. The results obtained here allow to assign unambiguously the carbon signal C^8 on the aromatic group. This assignment has been confirmed by recording the INADEQUATE 2D experiment of **5** in isotropic phase [19].

For compound **3** dissolved in the PCBLL/$CHCl_3$ (see Table 1), we find $|2T_{DH}|$ (=60 Hz) > $|T_{CH}|$ (=32 Hz), and hence the second "DHC" pulse sequence must be applied. If the expression of the NMR signals of the 2D map is identical to Eq. (9), the transfer function is further modulated by the evolution under the effect of the heteronuclear coupling between D^4 and H^7 nuclei during the effective period $\tau_1 - \tau_2 + \tau_3$. Thus we have:

$$f_{corr}(\tau_p) = 9 \times \left\{ \begin{array}{l} \sin[\pi^4 T_{D^2H^7}\tau_{DH}]\cos^2[\pi^4 T_{D^2H^7}\tau_{DH}] \\ \times \sin[2\pi^4 T_{D^2H^7}(\tau_1 - \tau_2 + \tau_3)] \\ \times (1 + 2\cos[2\pi^4 T_{D^4H^7}(\tau_1 - \tau_2 + \tau_3)])/3 \\ \times \cos^2[3\pi^2 D_{H^7H^7}(\tau_1 + \tau_2 + \tau_3)] \\ \times \cos[\pi^5 T_{H^5H^7}(\tau_1 + \tau_2 + \tau_3)] \\ \times \sin[\pi^1 T_{C^7H^7}(\tau_1 + \tau_2 + \tau_3)] \\ \times \sin[\pi^1 T_{C^7H^7}\tau_{CH}]\cos^2[\pi^1 T_{C^7H^7}\tau_{CH}] \end{array} \right\} \quad (12)$$

The "DHC" 2D map obtained for **3** when the defocusing and refocusing delays of "DHC" sequence are optimized for correlating deuteron D^2 to carbon C^7 is shown in Fig. 7b. Experimentally, no other correlation was observed. Note here the change of mesophase strongly modifies the solute orientation, and leads to invert the quadrupolar doublets associated with deuterons D^2 and D^6 compared with spectra shown in Figs. 4a and 5.

A possible extension of the "DHC" experiment consists of implementing a 90° pulse at the end of the refocusing delay of ^1H–^2H coupling (see Fig. 6c). Thus it becomes possible to transfer ^2H magnetization to a remote carbon atom through a pair of coupled protons. As in the case of the "DHC" sequence, the ideal values for τ_{DH} and τ_{CH} are equal to $1/|2T_{DH}|$ and $1/|2T_{CH}|$. During the τ_1 delay, the ^1H SQCs evolve under the effect of couplings, T_{DH} and T_{HH}, then the evolution of these coherences under the effect of couplings, T_{CH} and T_{HH}, proceeds for the effective periods $\tau_2 - \tau_3 + \tau_4$ and $\tau_2 + \tau_3 + \tau_4$, respectively.

The expression of the NMR signals for the "DHHC" correlation experiment is identical to Eq. (9). However the transfer function differs from that associated with the "DHC" experiment. For a "D^i–H^k_m–H^l_n–C^j" spin system, where m and n equivalent protons are weakly coupled, the analytical expression of $f_{corr}(\tau_{DH}, \tau_1, \tau_2, \tau_3, \tau_4, \tau_{CH})$ (noted hereafter $f_{corr}(\tau_p)$) is:

$$f_{corr}(\tau_p) = (n \times m)^2 \left\{ \begin{array}{l} \sin[\pi T_{D^iH^k}\tau_{DH}]\cos^{m-1}[\pi T_{D^iH^k}\tau_{DH}] \\ \times \sin[2\pi T_{D^iH^k}\tau_1]\cos^{m-1}[3\pi D_{H^kH^k}\tau_1] \\ \times \sin[\pi^1 T_{H^kH^l}\tau_1]\cos^{n-1}[\pi T_{H^kH^l}\tau_1] \\ \times \sin[\pi T_{C^jH^l}(\tau_2 - \tau_3 + \tau_4)] \\ \times \cos^{n-1}[3\pi D_{H^lH^l}(\tau_2 + \tau_3 + \tau_4)] \\ \times \sin[\pi T_{H^kH^l}(\tau_2 + \tau_3 + \tau_4)] \\ \times \cos^{m-1}[\pi T_{H^kH^l}(\tau_2 + \tau_3 + \tau_4)] \\ \times \sin[\pi T_{C^jH^l}\tau_{CH}]\cos^{n-1}[\pi T_{C^jH^l}\tau_{CH}] \end{array} \right\} \quad (13)$$

assuming that $\tau_2 = \tau_3 + \tau_4$ in order to eliminate the evolution under ^1H chemical shifts. In the simple case where $m = n = 1$, then the ideal values for the refocusing periods, τ_2, τ_3 and τ_4 are: $\tau_2 = 1/|4T_{HH}|$, $\tau_3 = 1/|4T_{HH}| - 1/|4T_{CH}|$ if

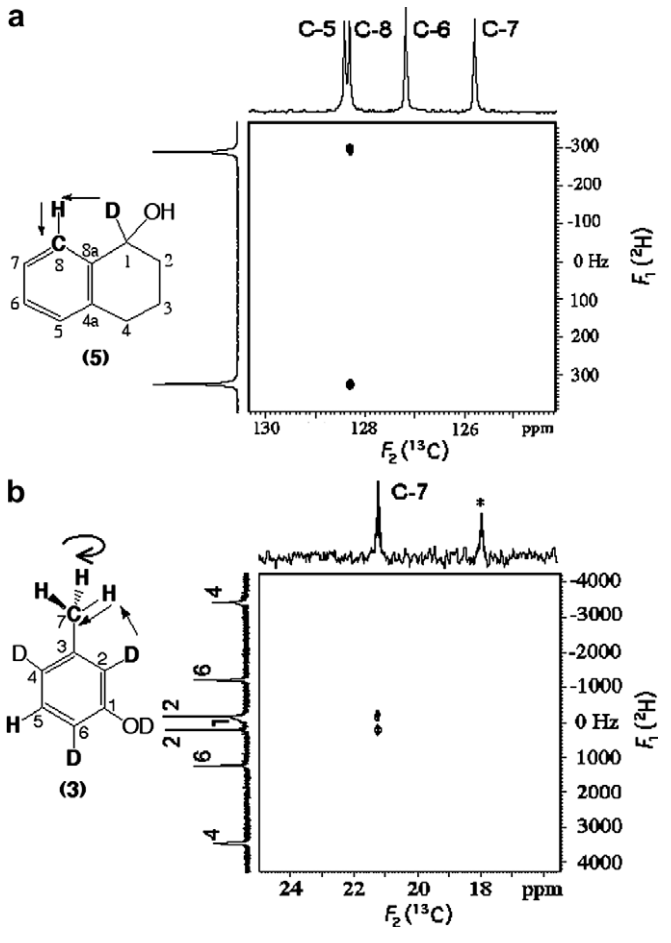

Fig. 7. Experimental 100.6 MHz "DHC" 2D spectra of **5** (a) and **3** (b) recorded in PBLG/$CHCl_3$ and PCBLL/$CHCl_3$ at 300 K. The 2D matrix is 128 (t_1) × 2048 (t_2) data points, with NS = 1024 for (a) and (b). The delays τ_{DH}, τ_1, τ_2, τ_3 and τ_{CH}, are equal to 56.5, 14.0, 12.8, 1.2 and 2.4 ms for (a) and 2.5, 8.2, 6.4, 1.8 and 6.2 ms for (b). The peak labelled with an asterisk corresponds to the ^{13}C signal of methyl group of ethanol used for stabilizing chloroform.

$T_{HH} < T_{CH}$ and $\tau_4 = 1/|4T_{CH}|$. The ideal value for delay τ_1 results in a subtle compromise between the defocusing of ^{1}H magnetization with the T_{DH} coupling and its refocusing with T_{HH} coupling. Mathematically, this value corresponds to the maximum of the function constituted by the four terms depending of τ_1 in Eq. (13).

From a relaxation point of view, we can show that $f_{corr}(\tau_p)$ depends on the following term:

$$\exp\left(-\tau_{DH}/T_2^{D^i}\right)\exp\left(-\tau_1/T_2^{H^k}\right)\exp\left(-(\tau_2+\tau_3+\tau_4)/T_2^{H^l}\right)\exp\left(-\tau_{CH}/T_2^{C^j}\right) \quad (14)$$

As previously, the T_2 relaxation will mainly affect the optimal value of τ_{DH}.

This kind of transfer has been tested on compound **5** where the H^7–H^8 *ortho* coupling is not null (≈33 Hz). Assuming that H^7 is also coupled with H^6, the transfer function, $f_{corr}(\tau_p)$, is equal to:

$$f_{corr}(\tau_p) = \left\{ \begin{array}{l} \sin[\pi^4 T_{D^1H^8}\tau_{DH}] \\ \times \sin[2\pi^4 T_{D^1H^8}\tau_1]\sin[\pi^3 T_{H^7H^8}\tau_1] \\ \times \sin[\pi^3 T_{H^7H^8}(\tau_2+\tau_3+\tau_4)] \\ \times \sin[\pi^1 T_{C^7H^7}(\tau_2-\tau_3+\tau_4)] \\ \times \cos[\pi^3 T_{H^6H^7}(\tau_2+\tau_3+\tau_4)] \\ \times \sin[\pi^1 T_{C^7H^7}\tau_{CH}] \end{array} \right\} \quad (15)$$

Fig. 8 shows the "DHHC" 2D correlation experiment obtained for **5** in the PBLG mesophase. As expected, only the correlation between D^1 and C^7 is observed on the map, thus allowing an easy assignment of ^{13}C signal for carbon 7. The result has been also confirmed using the analysis of the INADEQUATE experiment.

As in the case of "$D(H)_nD$" 2D experiment with $n > 2$, the 90° pulse used for ^{1}H relay could be replaced by a MLEV-17 sequence flanked with two trim pulses for performing a multiple proton relay.

2.6. Applications to a mixture of deuterated unlike/like stereoisomers

The initial goal of this work was to experimentally separate and assign the ^{2}H signals of *meso* compound and enantiomers in mixtures **1** and **2** oriented in a polypeptide mesophase. Experimentally, we have tested various oriented solvents made of PBLG or PCBLL dissolved in organic solvents such as $CHCl_3$ or DMF. For almost all of those mixtures, we have obtained four separated quadrupolar doublets. The NMR sample composition providing the best spectral discriminations for mixtures **1** and **2** is listed in Table 1. Unfortunately, even varying the composition (in wt%) or/and temperature of the sample, we were not able to detect ^{2}H–^{1}H couplings for the *meso* isomer and enantiomers neither in mixture **1** nor mixture **2**. The main reasons for the unsuccessful results are both the long distance between D–H in these molecules and the fast rotation of the lateral groups around the sp^2–sp^3 single bonds.

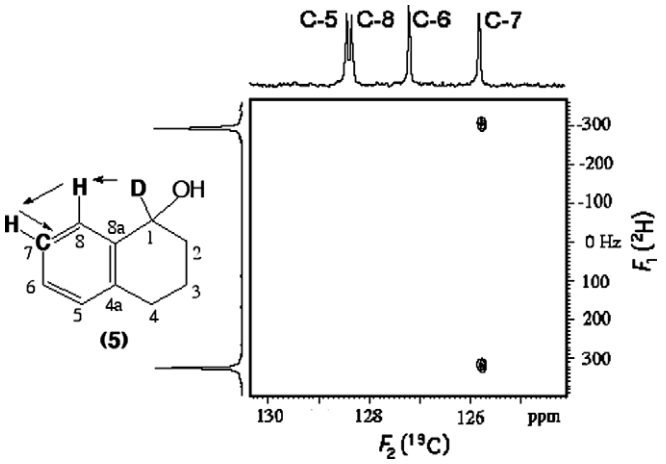

Fig. 8. Experimental 100.6 MHz "DHHC" 2D spectra of **5** in PBLG/$CHCl_3$ phase at 300 K. The 2D matrix is $100(t_1) \times 2048(t_2)$ data points with NS = 1024. The delays τ_{DH}, τ_1, τ_2, τ_3, τ_4 and τ_{CH}, are equal 56.5, 17.0, 3.5, 0, 3.5 and 7.0 ms, respectively.

These unsuccessful experimental results are rather frustrating even though numerical simulations using NMRSIM 4.3 software have shown the ability of "DHD" sequences to perform the assignment of a mixture of *u*/*l* stereoisomers.

To provide an illustrative example of the "DHC" 2D spectrum that could be experimentally obtained under ideal conditions, Fig. 9 presents the simulated "DHC" 2D map of mixture **2** centred on the C^6 aromatic carbon site if the all corresponding ^{13}C signals were spectrally discriminated (namely three resonances). The two doublets of the *meso* compound were arbitrarily chosen as being the two external ones of the ^{2}H 1D spectrum. In this case, the two quadrupolar doublets correlated to the same ^{13}C peak belong to the *meso* (peaks labelled by open and solid squares on the 2D map).

Experimentally, only two ^{13}C signals (122.0 and 122.2 ppm) were observed for C^6 due to the overlap of ^{13}C peaks of the *unlike* and of one of the *like* isomers. Consequently, it would not be possible to assign directly the signals from the analysis of the "DHC" 2D map as in Fig. 9. To this end, we would have to record the ^{2}H spectrum of mixture **2** in an achiral mesophase, noted PCBL (or PBG) made by adding equal amount of PCBLL (PBLG) and PCBDL (PBDG), its enantiomer [6]. In this achiral medium, any spectral enantiodiscrimination is eliminated, and hence the magnitude of ^{2}H quadrupolar doublets or the ^{13}C chemical shift values measured in this medium correspond to the algebraic average of values measured in the chiral mesophase. Collapsing of the ^{13}C signals belonging to the *RR* and *SS* compounds should result and so we would obtain a 2D map where two ^{2}H doublets in the F_1 dimension, one for the *meso* and one for the *RR*/*SS* isomers ($|\Delta\nu_Q^{RR,SS}| = 87$ Hz/$|\Delta\nu_Q^{meso}| = 342$ Hz), would be correlated with two ^{13}C peaks of equal intensity in the F_2 dimension. The magnitude of $\Delta\nu_Q$s measured in the achiral mesophase would allow the assignment of the two doublets belonging to the *meso* derivative and *RR*/*SS* isomers.

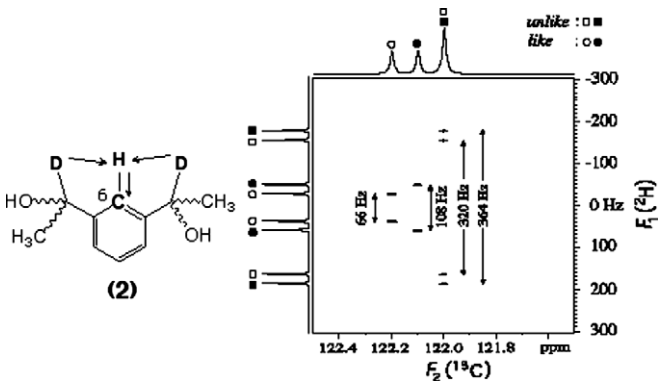

Fig. 9. Simulated 100.3 MHz "DHC" 2D spectrum of mixture **2** dissolved in a chiral mesophase when ^{2}H and ^{13}C signals (aromatic carbon 6) for each stereoisomer are spectrally discriminated. ^{2}H quadrupolar splittings and ^{13}C chemical shifts used for those simulations are similar to the values measured on experimental ^{2}H–{^{1}H} and ^{13}C–{^{1}H} 1D spectra of mixture **2** dissolved in the PCBLL/$CHCl_3$ phase at 317 K. The parameters τ_{DH}, τ_1, τ_2, τ_3 and τ_{CH}, are equal to 250, 36.5, 35.3, 1.2 and 2.4 ms (i.e. $|^1T_{CH}| = 208$ Hz). The sign of quadrupolar splittings for the *meso* compound and enantiomers are assumed to be the same (positive or negative).

3. Conclusions

This methodological work describes several 2D NMR strategies dedicated to the analysis of ^{2}H spectra of a mixture of deuterated *u/l* aromatic compounds using weakly ordering chiral oriented solvents. We have designed various homo- and heteronuclear 2D experiments such as the "$D(H)_nD$" or "$D(H)_nC$" correlation experiments (with $n = 1, 2$) towards this goal. Series of experiments on model compounds have demonstrated the efficacy of the various sequences proposed here even if the initial aim was not experimentally reached. These new 2D pulse sequences are based on INEPT-type polarization transfers, but DEPT-type schemes should also induce efficient heteronuclear transfers. We are currently engaged in exploring such an alternative.

Another possible improvement of the sequences proposed here could consist in eliminating ^{1}H–^{1}H strong couplings or reducing the magnitude of ^{1}H–^{1}H couplings between the proton(s) used as relay and other protons in the molecule in order to reduce the dispersion of ^{1}H magnetization through useless protons. This could be performed by introducing multiple-pulse homonuclear decoupling sequences such as "FF-16" or "BLEW-48" sequences in periods where ^{1}H magnetization evolves under the effect of ^{1}H–^{1}H couplings between the proton(s) used as relay and other protons in the molecule [20–23].

4. Experimental

4.1. Synthesis of compounds

The synthesis of mixtures **1** and **2** can be found in Ref. [6], while compound **3** is commercially available from Isotec Company.

The 2,4,6-trideutero-3-methylphenol, **4**, was prepared using the following procedure. The 3-methylphenol was selectively deuterated to 2,4,6-trideutero-3-methylphenol by repeated exchange in 10% DBr in D_2O under reflux for 10 h. After evaporation of the DBr/D_2O the residue was dissolved in ether and the phenolic hydroxy-group was back exchanged by extraction with H_2O, the ether phase was dried, the solvent evaporated and the deuterated compound was distilled under reduced pressure in a bulb-tube. The degree of deuteration was checked by NMR in $CDCl_3$/TMS and was found better than 96%. Compound **5** was prepared enantiomerically enriched using the asymmetric reduction method developed by Mosher et al. [24].

The description of NMR sample preparation can be found in Ref. [2,3]. Exact composition of each sample is given in Table 1.

4.2. NMR spectroscopy

The 2D experiments were performed on Bruker DRX high-resolution spectrometers at 14.1 T and 9.4 T. The first one is equipped with a 5-mm selective ^{2}H cryogenic probe. The second one is equipped with a 5-mm four-channel probe (QXO). This probe allows the matching and tuning of the deuterium channel (outer coil), but the ^{2}H channel (lock) of any probes (dual or broadband) can be used to perform such experiments [9]. The temperature of the sample was controlled by the standard variable temperature unit of the spectrometer and the experiments were performed without sample spinning. All 2D matrices were zero-filled to $1k\,(t_1) \times 2k\,(t_2)$ data points prior to the double Fourier transformation. For all sequences, the full phase cycling is obtained by applying the CYCLOPS procedure to the basic phase cycling given in figure caption, and the quadrature detection in the F_1 dimension uses the TPPI method. All experiments reported here lead to a NMR signal modulated in phase due to the the evolution under the effect of quadrupolar splittings during some of the re- and defocusing periods in the sequences. Hence, 2D contour plots have to be displayed in magnitude mode. In 2D maps, the projections reported correspond to the respective 1D spectra. Other experimental NMR parameters or details are given in the figure captions.

The simulated "DHC" spectrum was calculated using NMRSIM (4.3) program included in the TOPSPIN software (1.3) developed by Bruker Biospin. The 2D matrix was made of $512(t_1) \times 1024(t_2)$ data points with $NS = 8$. Neither zero-filling nor filtering window were applied prior to the double FT.

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