Homonuclear decoupling of 1H dipolar interactions in solids using heteronuclear recoupling[1]

Greg L Olsen[1], Adonis Lupulescu[1], Jean-Nicolas Dumez[1,2], Lyndon Emsley[2], and Lucio Frydman[1]

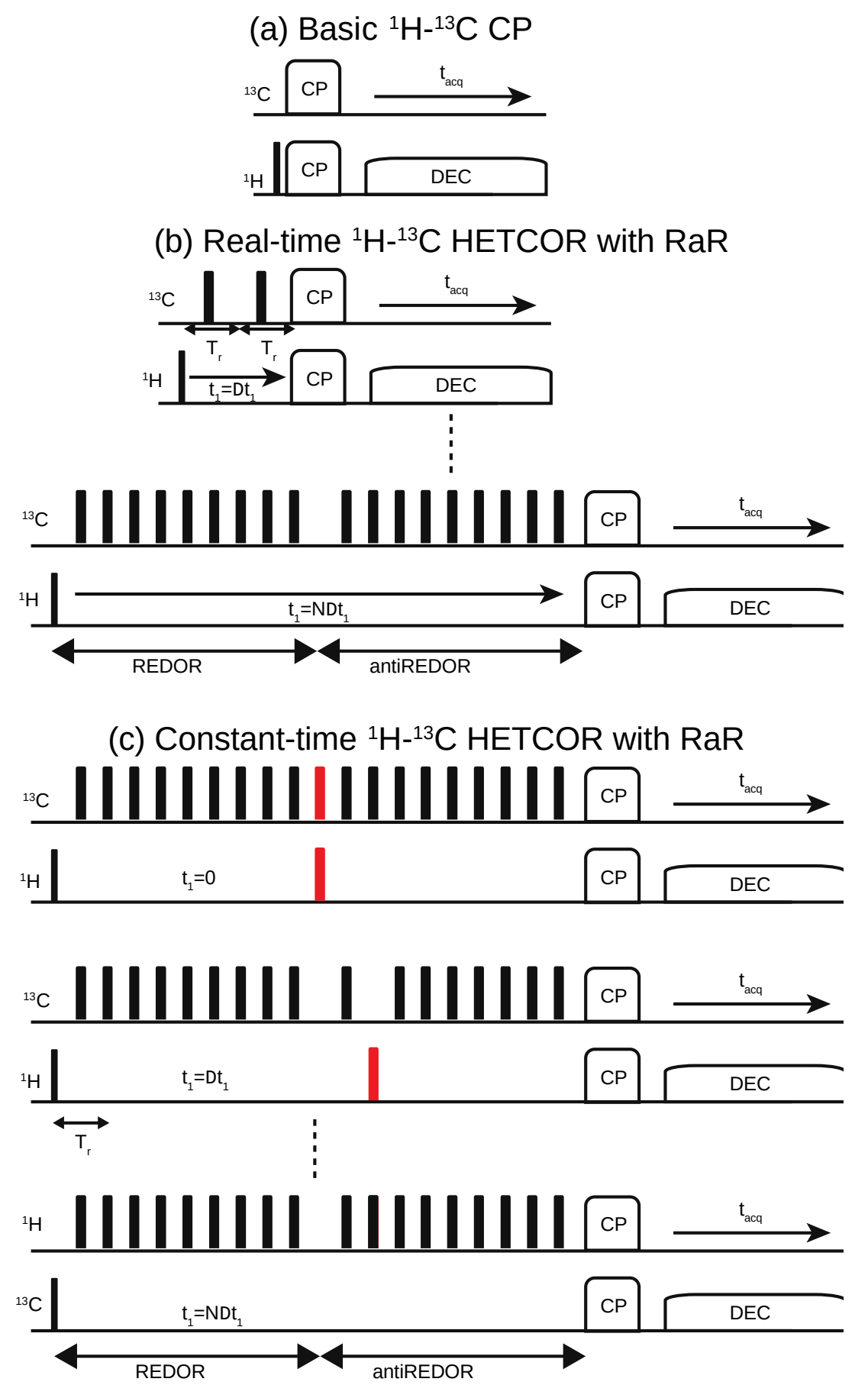
[1]Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel. , [2] Université de Lyon (CNRS / ENS-Lyon / UCB Lyon 1), Centre de RMN à Très Hauts Champs, 5 rue de la Doua, 69100 Villeurbanne, France

Abstract

Line narrowing in solid state ^1H NMR has traditionally been achieved by applying pulse sequences that combine multiple-pulse RF irradiation with magic-angle-spinning (MAS) to effectively average away the dipole-dipole homonuclear Hamiltonian. The present study explores a new alternative that departs from the usual concept of directly acting on the strongly coupled spins with radiofrequency (RF) pulses; instead, we seek to achieve a net homonuclear dipolar decoupling in solids by exploring the *reintroduction* of MAS-averaged *heteronuclear* dipolar couplings between the protons and directly-bonded ^{13}C or ^{15}N nuclei. This "Recoupling-antiRecoupling" (RaR) scheme relies on the recoupling of the dipolar interaction with heteronuclear spins, which under fast MAS will exceed the strength of – and thus not commute with – the homonuclear ^1H-^1H coupling one intends to average out. A subsequent removal ("antiRecoupling") of these heteronuclear interactions can lead to narrowed proton resonances, without ever pulsing on the ^1H channel. The line-narrowing properties of RaR are illustrated here with numerical simulations and experiments on model organic solids.

Introduction

Heteronuclear X-^1H couplings are utilized in multiple ways in both liquid- and solid state NMR – for example, as means to enhance the low-gamma spin nuclear polarization, to provide information about molecular structure, or to investigate alignment and dynamics. Seldom, however, have heteronuclear couplings been used to improve the resolution of NMR spectra – particularly the proton spectral resolution. Recently we have shown how the BIRD (BIlinear Rotation Decoupling[2,3]) concept can be implemented to exploit ^{13}C-^1H couplings to achieve the desired proton-proton decoupling in *one*-dimensional solution experiments[4]. Here we explore whether, as in liquids, the resolution of solid state ^1H NMR spectra on organic compounds can be improved by *reintroducing* X-^1H dipolar couplings. A series of new experiments at high MAS frequencies were thus carried out, in which ^{13}C-^1H dipolar couplings are reintroduced in order to truncate the partially averaged ^1H-^1H interactions – and in this way achieve ^1H-^1H decoupling in the solid state *without proton pulsing*.



Pulse sequences

During the 1H evolution period of the 2D HETCOR experiments, a recoupling pulse sequence is applied to reintroduce the heteronuclear 1H-13C dipolar interaction, which in turn truncates the flip-flop term of the homonuclear 1H-1H interaction. The reduced, inhomogeneous interaction is then better suppressed by magic-angle spinning. The sign of the recoupled interaction is changed halfway through the evolution period to refocus its effect.

Shown here are REDOR-based implementations of RaR in which 'REDOR-antiREDOR' decoupling has been used during the 1H evolution period. Real-time (b) and constant-time (c) versions of these sequences are shown. The first, second and last increments are shown for a sequence with a maximum evolution time of 10 rotor periods.

Figure 1. Pulse sequences used in this study. The RaR experiments shown here use REDOR-antiREDOR decoupling during the 1H evolution period of a 1H-13C HETCOR.

Methods and Materials

Experiments shown here were performed on a custom-made tripeptide sample [U-^{13}C,^{15}N]-LAF (leucine-alanine-phenylalanine), on a 600 MHz Varian VNMRS spectrometer, using a 1.6 mm triple-resonance Varian probe. ^1H-^{13}C HETCOR spectra were recorded to compare the pulse sequences illustrated in Fig. 2.

Real-time HETCOR experiments (fig. 1b) were performed at a spinning frequency of 35714 Hz. Acquisitions incorporating RaR were compared against analogous recoupling-free versions in which evolution periods consisted of simple free evolution (fig. 1b) (25 increments of 2 t_R in the indirect dimension, total acquisition time 1.2 h.)

Constant time HETCOR spectra (fig. 1c) were recorded at a spinning frequency of 39062 Hz (22 increments of 4 t_R in the indirect dimension; total acquisition time of 1.8 h.) As for the R.T. versions, evolution periods in these constant-time implementation consisted of either (1) a free evolution period, or (2) an RaR block.

For the RaR blocks, a ^{13}C nutation frequency of 192 kHz was used for the refocusing pulses. In all experiments the indirect-domain ^1H evolution period was followed by a short cross-polarization period (contact time 60 ms), enabling a site-specific $^1H \rightarrow ^{13}C$ polarization transfer step. Heteronuclear decoupling employed a train of 180 pulses during acquisition[5], as this proved superior at these fast spinning rates.

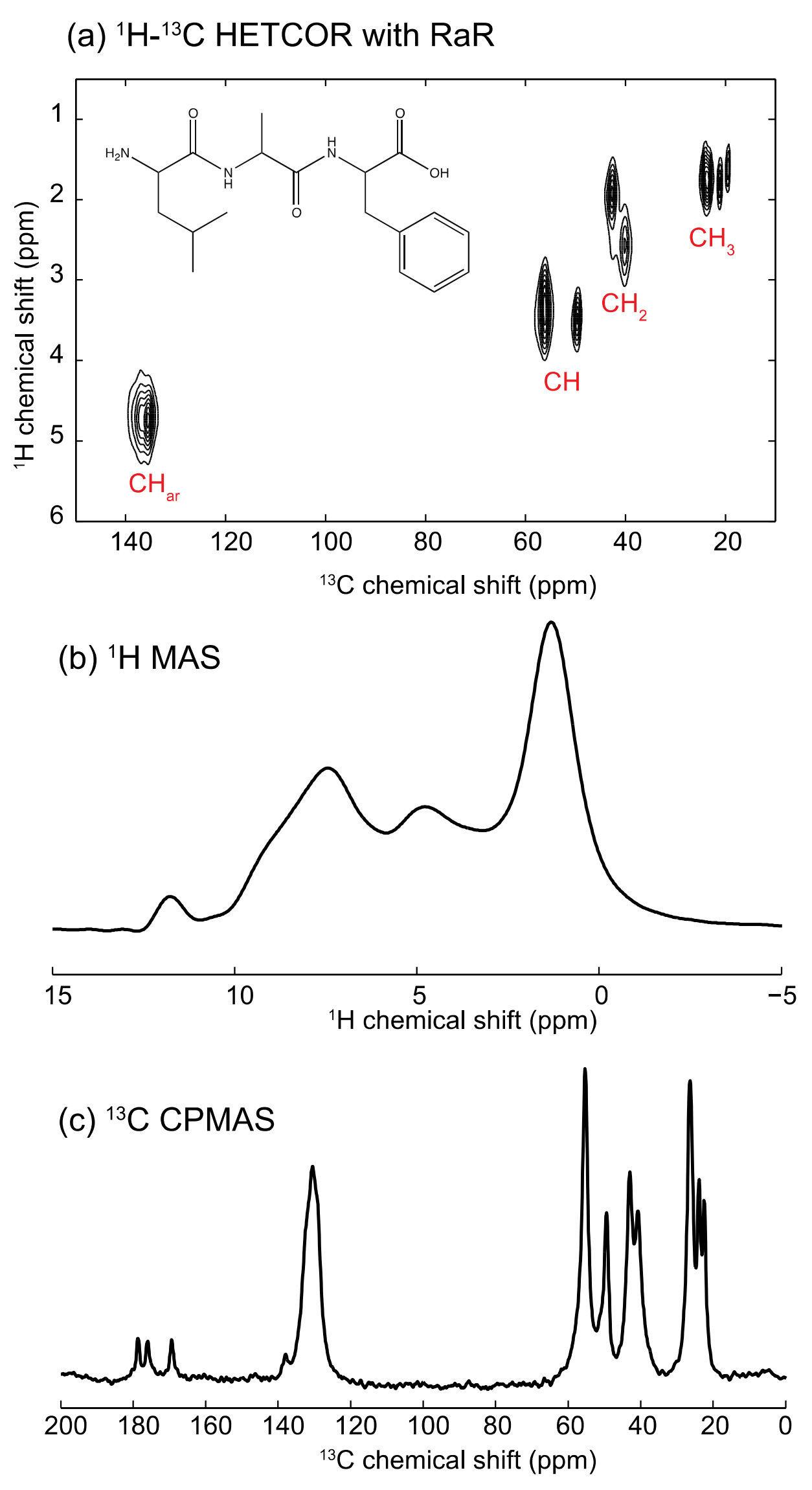


Figure 3. (a) 2D ^1H-^{13}C HETCOR spectrum obtained for the tripeptide U[^{13}C,^{15}N]LAF using RaR decoupling during evolution. The chemical structure of LAF is shown as an inset. The 1D ^1H MAS (b) and ^{13}C CPMAS spectra (c) of U[^{13}C,^{15}N]LAF are also shown.

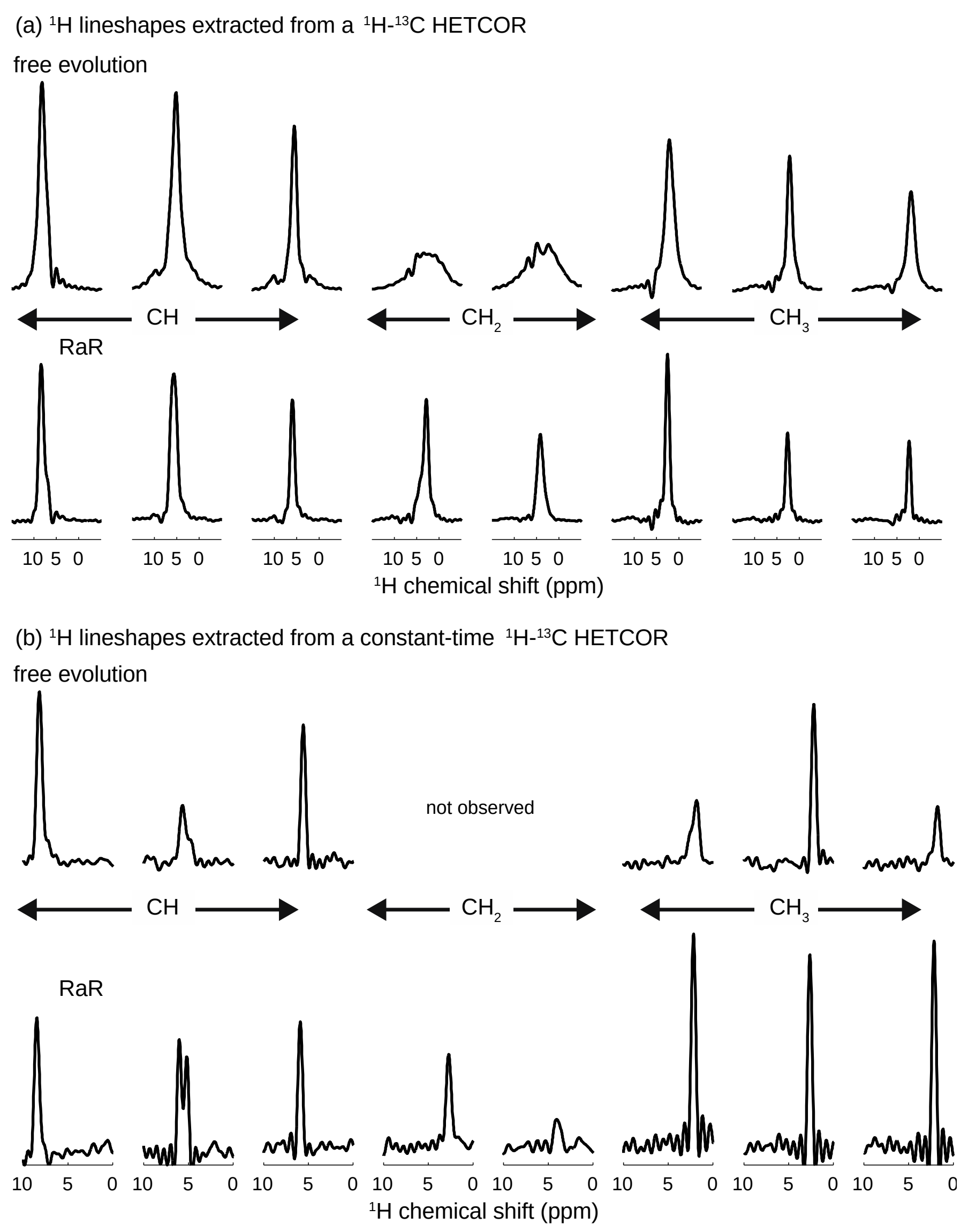


Figure 4. Comparison of lineshapes obtained in real-time (a) and a constant time (b) 2D 1H-13C HETCOR experiments on U[13C,15N]LAF with application of RaR or a free evolution period.

Results

1D proton, 1D carbon, and 13C-1H HETCOR (with RaR evolution) spectra are shown in figure 2. Linewidths for the various carbon-proton types observed in LAF are shown in figure 3 and listed in table 1. Significant reduction of proton line-widths were observed in two-dimensional versions of such experiments, especially for CH2 protons. Note that in contrast to classical decoupling sequences, there is no scaling of the ^1H chemical-shift dimension. These experiments confirm the line-narrowing mechanism observed in simulations (not shown); where line narrowing is similarly dramatic for CH_2 groups.

Chemical Shift (ppm)	Atom type	Linewidth (Real-time; kHz)		Linewidth (Const.-time; kHz)	
		Free	RaR	Free	RaR
130	CH_{aro}	1.1	0.9	580	400
53	CH^a	1.3	1.1	(Not resolved)	(resolved)
46	CH^b	0.9	0.7	380	330
40	$CH2^a$	5	0.8	(Not observed)	400
38	$CH2^b$	5	1	(Not observed)	570
23	$CH3^a$	1.4	0.7	680	360
21	$CH3^b$	0.9	0.7	380	330
19	$CH3^c$	1.2	0.6	420	320

Table 1. Experimental 1H linewidths obtained with real-time and constant-time 2D 1H-13C HETCOR experiments on U[13C,15N]-LAF with RaR or a free evolution period.

Discussion and Conclusions

The RaR mechanism relies on a strong heteronuclear dipolar interaction to truncate the homonuclear dipolar interaction. In organic solids, only directly bonded pairs are expected to have a sufficiently strong dipolar coupling. As a result, when 13C spins are used as ancillary spins, only 13C-bonded protons will be efficiently decoupled. The related concept of using 1H-bonded ancillary spins to decouple the 1H-1H interaction can be found in solution-state NMR in sequences that exploit BIlinear Rotation Decoupling (BIRD). In the case of 13C-aided decoupling for natural-abundance compounds, RaR is best employed in the evolution period of a 13C-detected correlation experiment, which ensures that only decoupled protons are observed. The limitation in sensitivity is then intrinsic to the correlation experiments and does not come as an additional cost due to RaR decoupling.

In summary, we have shown how the effective 1H-1H dipolar interactions can be reduced in MAS experiments with no direct RF manipulation of the protons. The Recoupling-antiRecoupling scheme relies on the heteronuclear dipolar interaction to truncate the homonuclear dipolar interaction. Its line-narrowing properties have been demonstrated in numerical simulation and 2D 1H-13C correlation experiments. RaR decoupling has the significant advantage of leaving the 1H chemical-shift interaction unchanged. As it relies on an entirely new mechanism, it may open the way to a new class of homonuclear dipolar decoupling sequences.

Contact:

Lucio.Frydman@weizmann.ac.il
Website: http://www.weizmann.ac.il/chemphys/Frydman_group/home.html

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