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Supporting information for manuscript

Real-time reaction monitoring by ultrafast 2D NMR on a benchtop spectrometer

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1. Ultrafast NMR experiments

1.1 Spectrometers

400 MHz spectrometer. The spectra shown in Fig. 1A and B were recorded on a Bruker Avance I 400 spectrometer operated with Topspin 2.1, at a frequency of 400.13 MHz with a 5 mm dual probe equipped with a z-axis gradient generating a maximum field gradient of 0.80 T/m.

43 MHz benchtop spectrometer. The experiments performed at low-field were recorded on a Spinsolve from Magritek working at a frequency of 43.62 MHz, equipped with a gradient coil along the B_0-axis (i.e. along the transverse plane of the NMR tube) which can generate a maximum field gradient of 0.16 T/m and operated with the Prospa Software.

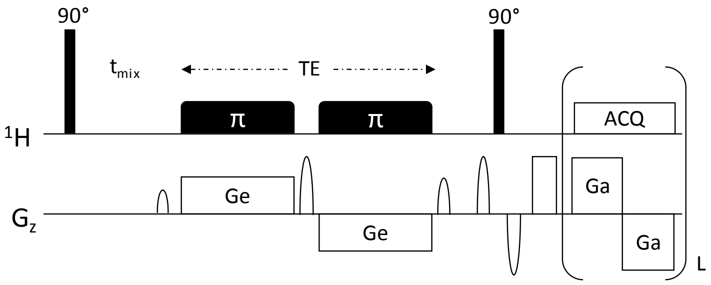
1.2 Experiment at high-field

UF COSY single scan. The experiment at 400.13 MHz presented in Fig. 2B was recorded in 109 ms with the homemade pulse sequence of Figure S1, consisting in a spatial encoding followed by a hard 90° pulse as mixing period and by echo-planar detection. The spatial encoding was performed in a constant-time phase-modulated fashion based on a double spin echo scheme,[1] with two 15 ms smoothed chirp pulses (i.e. TE=30 ms) swept over a 13 kHz range. The amplitude of the encoding gradients Ge was adapted to obtain a frequency dispersion equivalent to the frequency sweep of the pulses, corresponding to 2.28% of the maximum gradient strength available. During the acquisition, 128 pairs of bipolar gradient pulses were applied (90% of maximum strength, 294.4 µs each, separated by a 20 µs delay). Conventional coherence-selection gradients were also used. The spectrum was processed using a home-written routine in Matlab, including an optimized Gaussian apodization in the spatially-encoded dimension[2] and a sine-bell apodization in the FT dimension. In all the spectra, the indirect domain is called “ultrafast dimension” since it results from spatial-encoding without FT, whereas the direct dimension -arising from a conventional evolution during the detection period- is called “conventional dimension”.

1.3 Experiment at low-field

UF COSY single scan. The experiment at 43.62471 MHz presented in Fig. 2E was recorded in 400 ms with the homemade pulse sequence of Figure S1, consisting in a spatial encoding followed by a hard 90° pulse as mixing period and by echo-planar detection. The spatial encoding was performed in a constant-time phase-modulated fashion based on a double spin echo scheme, with two 30 ms smoothed chirp pulses (i.e. TE=60 ms) swept over a 3.5 kHz range. The amplitude of the encoding gradients Ge was adapted to obtain a frequency dispersion equivalent to the frequency sweep of the pulses, corresponding to 11.6% of the maximum gradient strength available. A delay t_{mix} of 42 ms was added prior to the spatial encoding step in order to optimize the effects of J-modulation arising from the constant-time nature of the double spin-echo encoding.[3] During the acquisition, 128 pairs of bipolar gradient pulses Ga were applied (85% of maximum strength, 1280.4 µs each). The desired coherence selection was obtained as described in Figure S1. The spectrum was processed using a home-written routine in Prospa, including an optimized Gaussian apodization in the spatially-encoded dimension and a sine-bell apodization in the FT dimension. In all the spectra, the indirect domain is called “ultrafast dimension” since it results from spatial-encoding without FT, whereas the direct dimension -arising from a conventional evolution during the detection period- is called “conventional dimension”.

Fast hybrid UF COSY. The UF spectra COSY for the reaction monitoring (Fig. 2B-D) were recorded in 146 s (i.e. 36 scans) with the homemade pulse sequence of Figure S1. The sequence was similar to the previous UF COSY with the following features. The spatial encoding was performed by combining two 45 ms smoothed chirp pulses (i.e. TE=90 ms) swept over a 3.5 kHz range with encoding gradients Ge fixed at 9.00% of maximum gradient strength. The detection was then achieved with 128 pairs of bipolar gradient pulses Ga at 85% of maximum strength (1280 µs each). The desired coherence-selection was obtained thanks to both a standard four step phase cycling and selecting gradient pulses. The spectrum was processed in the same way as previously described.



Supplementary figure S1. Pulse sequence of the UF COSY achieved with a constant-time and phase-modulated spatial encoding.

2. Numerical simulations

The simulations shown in Fig. 1C and F were performed thanks to a simulation platform that we recently introduced,[3] based on the Fokker-Planck theory module implemented in version 2.0 of Spinach library.[4]

2.1 Simulation of UF COSY at 400 MHz

The spectrum presented in Fig. 1F was simulated with the following features. Acquisition parameters: 512 points separated by a dwell time of 0.575 µs were used to compute the UF dimension whereas the conventional one was obtained with 128 loops in the detection block. The acquisition gradients were fixed at 0.800 T/m. For the encoding parameters, encoding gradients of 0.020 T/m were applied while the π-chirp pulses were performed by a WURST pulse built with 1000 points, sweeping a bandwidth of 13 kHz in 15 ms. The second chirp of the double spin echo is flanked by two crushers. The CTP was completed in the same way as in supplementary figure S1 via gradient pulses at 0.48 T/m. The length of the sample was fixed at 1.5 cm and the Liouvillian propagation was performed over 500 z-positions. Here a B_0 field of 9.416 T was considered and ideal pulses were assumed. The simulated 2D FID was then processed thank to a home-written procedure in Matlab: a sinusoidal apodization for the conventional dimension while a Gaussian apodization was applied in the UF dimension, including zero filling in both dimensions.

2.2 Simulation of UF COSY at 43 MHz

The spectrum presented in Fig. 1C was simulated with the following features. Acquisition parameters: 256 points separated by a dwell time of 5.000 µs were used to compute the UF dimension whereas the conventional one was obtained with 128 loops in the detection block. The acquisition gradients were fixed at 0.117 T/m. For the encoding parameters, encoding gradients of 0.016 T/m were applied while the π-chirp pulses were performed by a WURST pulse built with 1000 points, sweeping a bandwidth of 3.5 kHz in 30 ms. The second chirp of the double spin echo is flanked by two crushers. The CTP was completed in the same way as in supplementary figure S1 via gradient pulses at 0.48 T/m. The length of the sample was fixed at 0.5 cm and the Liouvillian propagation was performed over 500 z-positions. Here a B_0 field of 1.010 T was considered and ideal pulses were assumed. The simulated 2D FID was then processed thanks to a home-written procedure in Matlab: a sinusoidal apodization for the conventional dimension while a Gaussian apodization was applied in the UF dimension, including zero filling in both dimensions.

3. Procedure of the Heck-Matsuda reaction

t-BuONO (0.317 mmol, 38 µL) was added to a solution of aniline (0.252 mmol, 38.8 mg) in MeOH (0.450 mL). The resulting mixture was stirred and transferred into an NMR tube. Methyl acrylate (0.555 mmol, 50 µL) and palladium acetate (1.7 mol%, 1.1 mg) in MeOH (0.200 mL) were added to the solution. The bicatalytic reaction was then initiated by adding methanesulfonic acid (30 mol%, 5 µL). The NMR tube was stirred and inserted inside the benchtop NMR at 29°C for 144 min.

4. References

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