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A Simple NMR-Based Method for Studying the Spatial Distribution of Linkers within Mixed-Linker Metal–Organic Frameworks**

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Abstract: *The spatial distribution of different linkers within mixed-linker metal–organic frameworks crucially influences the properties of such materials. A simple and robust approach based on ^1H spin-diffusion magic-angle-spinning nuclear magnetic resonance measurements and modeling of spin-diffusion curves is presented; this approach facilitates the distinction between homogeneous and clustered distributions. The performance of the approach is demonstrated with an example of an aluminum-based metal–organic material DUT-5, which has framework consisting of biphenyl and bipyridyl dicarboxylic linkers. The distribution is shown to be homogeneous in this material. The approach could be applied to studying other spatially disordered crystalline materials.*

One of the key advantages of metal–organic framework materials (MOFs) over other porous materials is the versatility of their frameworks, which can be prepared from many different organic linkers and can be functionalized with many different functional groups. Even a single-phase MOF can contain various linkers or functional groups. For example, Deng et al. prepared a series of MOFs by mixing differently modified terephthalic acids bearing H, NH_2, Br, Cl, NO_2, $(CH_3)_2$, C_4H_4, $(OC_3H_5)_2$, and $(OC_7H_7)_2$ groups in different relative amounts and combinations.[1] With this approach, 18 MOFs (multivariate or mixed-linker MOFs), isostructural with MOF-5, with up to eight distinct functionalities in one phase were synthesized. It was shown that selectivity of such mixed-linker MOFs crucially depended on the way the different linkers or functional groups were distributed throughout the crystals. For example, an alternating apportionment of two linkers in mixed-linker MOF-5 gave four times better selectivity for CO_2 over CO than the clustered apportionment or the single-linker counterparts.

When preparing new mixed-linker MOFs, often too little attention is given to the precise characterization of the distribution of different linkers. The incorporation of linkers into the frameworks is usually inspected by simple ^{13}C and/or ^1H NMR spectroscopy; the value of the isotropic chemical shift of the carboxyl ^{13}C signal and/or the absence or presence of the carboxylate ^1H signal supposedly proves or disproves the incorporation of the organic linker into the framework.[2] Deng et al. took this one step further and divided large single crystals of mixed-linker MOF-5 into three equal segments and determined the fractions of different linkers in the segments.[1] Because the relative ratios of various linkers did not change appreciably from one segment to another, they concluded that macroscopic domains consisting of only one type of linker were not formed in the particular MOF-5.

The most detailed study of mixed-linker MOFs was presented by Kong et al.[3] They isotopically labeled various linkers used in the synthesis of MOF-5 with ^{15}N and carried out demanding ^{13}C–^{15}N REDOR NMR measurements, which provided information on the average distances among different linker molecules. By comparing the results of the REDOR measurements with results from Monte Carlo simulations, they were able to discriminate between cases where linkers of one type formed homogeneous domains within crystals, where different linkers were alternating with one another in the framework, and where different linkers were distributed randomly throughout the crystalline framework. This valuable information helped them rationalize the observed differences in adsorption capacity and separation efficiency of mixed-linker MOFs characterized by different types of linker distributions. Although powerful, the described procedure is very demanding and expensive, and it is impossible to routinely employ it for inspecting all the promising mixed-linker MOFs prepared in many laboratories.

Herein, we show that a relatively simple NMR method that does not require isotopic labeling can also provide valuable insight into the composition of mixed-linker MOFs. The proposed approach is based on ^1H spin-diffusion NMR measurements and modeling. To demonstrate this approach, we selected DUT-5 MOF[4] in which chains of AlO_6 octahedra are through biphenyl dicarboxylic acid (BPDC) linkers connected into a porous framework with the topology of MIL-53.[5] The mixed-linker DUT-5 (ML-DUT-5) was prepared by replacing part of the BPDC molecules with molecules of bipyridyl dicarboxylic acid (BPyDC) in the synthesis mixture. The two linkers differ from each other only in site 1 in the aromatic ring; the C1–H1 pair of BPDC is replaced with N in BPyDC (Scheme 1). Our synthesis

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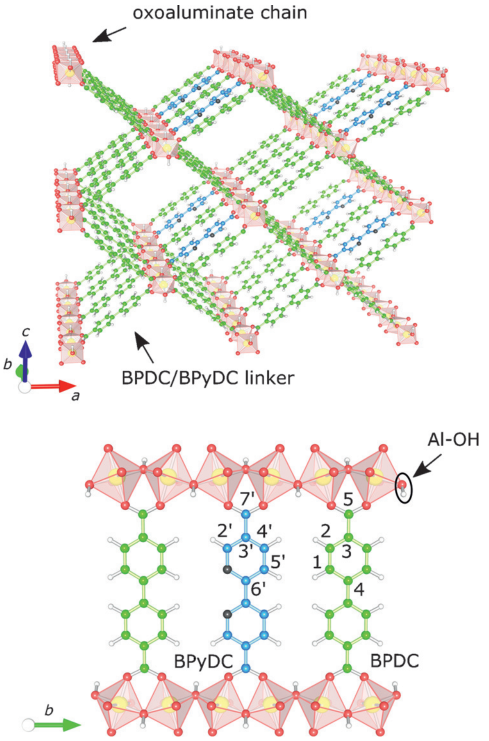
Supporting information for this article (including details of NMR experiments, synthesis, adsorption measurements, X-ray diffraction, DFT/GIPAW calculations, and modeling of ^1H spin-diffusion curves) is available on the WWW under http://dx.doi.org/10.1002/anie.201504426.



Scheme 1. Structure and labeling of carbon and hydrogen atoms of ML-DUT-5. Labels of a carbon atom and of a hydrogen atom attached to this carbon include equal numbers (for example, hydrogen atom attached to C1 is labeled H1).

procedure yielded ML-DUT-5 in which about 12 % of BPDC was substituted by BPyDC (Supporting Information). X-ray diffraction and N_2 sorption measurements indicated that ML-DUT-5 exhibited the same framework topology and approximately the same specific surface area as the original single-linker DUT-5.

Incorporation of BPyDC into the framework of DUT-5 was thoroughly studied by NMR spectroscopy. In the ^{1}H–^{13}C CPMAS NMR spectrum of ML-DUT-5 (Figure 1), five strong and five weak signals can be resolved. The contributions between 120 and 160 ppm belong to carbon atoms of the aromatic rings of BPDC and BPyDC, and the two overlapped signals at 172 ppm belong to carboxyl carbon atoms of the two different linkers. Because the carboxyl groups of BPyDC resonate very closely to the carboxyl groups of BPDC, the local environments of the carboxyl groups of the two different linkers have to be similar, suggesting that BPyDC molecules are indeed attached to the oxoaluminate chains of DUT-5 in the same way as BPDC molecules. In the ^{1}H MAS NMR spectrum of ML-DUT-5, four signals can be resolved; the signal at 3.0 ppm belongs to the bridging OH groups of the inorganic oxoaluminate chains, and the signals at 7.7 and 8.4 ppm belong to hydrogen atoms of the aromatic rings of the linkers. An additional weak signal at 9.5 ppm can probably be assigned to the H2′ hydrogen atom of the BPyDC linker. The contributions of other hydrogen atoms of BPyDC cannot be resolved; they presumably overlap with the strong signal of BPDC at 8.4 ppm.

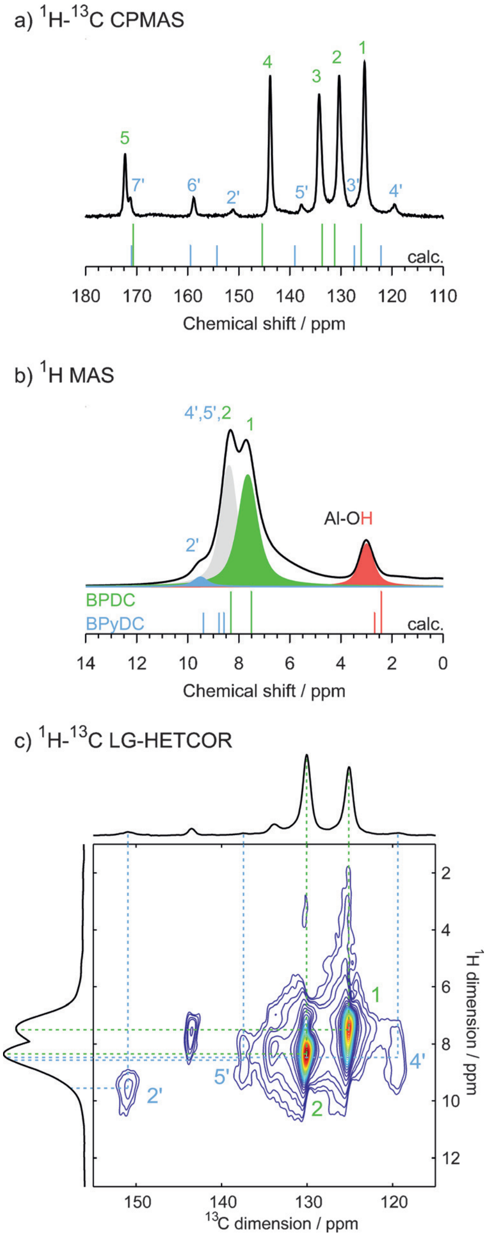


Figure 1. a) ^{1}H–^{13}C CPMAS, b) ^{1}H MAS, and c) ^{1}H–^{13}C LG-HETCOR NMR spectra of ML-DUT-5. Vertical marks in (a) and (b) mark the calculated ^{13}C and ^{1}H isotropic chemical shifts. Long and short tics correspond to structural models of DUT-5 containing only BPDC and BPyDC linkers, respectively. Two-dimensional NMR spectroscopy and chemical shift calculations enabled successful assignment of ^{1}H MAS NMR signals and revealed that one peak belonging only to BPyDC (H2′) can be clearly resolved from one peak belonging only to BPDC (H1).

Correct assignment of ^{13}C and especially of ^{1}H NMR signals is very important for our later analysis. Therefore, an additional ^{1}H–^{13}C LG-HETCOR[6] NMR experiment was conducted, and ab initio DFT/GIPAW[7,8] calculations of ^{13}C and ^{1}H isotropic chemical shifts were carried out. The ^{1}H–^{13}C LG-HETCOR NMR spectrum of ML-DUT-5 in Figure 1c shows that ^{1}H signals at 7.7 and 8.4 ppm belong to the H1 and H2 hydrogen atoms of BPDC, respectively. The spectrum also confirms that the proton signal at 9.5 ppm belongs to the H2′ hydrogen atoms of BPyDC and shows that the remaining hydrogen atoms of BPyDC (H4′ and H5′) resonate at about 8.4 ppm. The assignment of the 3.0 ppm signal to the bridging OH groups is confirmed by the ^{27}Al–^{1}H HETCOR experiment (Supporting Information, Figure S6).

The detected ^{1}H and ^{13}C chemical shifts match the values that were obtained by ab initio DFT/GIPAW calculations (Figure 1). The chemical shifts were calculated based on two similar structural models, one for the DUT-5 framework containing only BPDC linkers and another for the DUT-5 framework containing only BPyDC linkers. The agreement between the experiment and calculation supports the assignment of NMR signals derived from the LG-HETCOR experiment and provides another indication that BPyDC linkers are incorporated into the DUT-5 framework.

After confirming that both BPDC and BPyDC are incorporated into the framework of ML-DUT-5, we can inspect the nature of the distribution of the two linkers within the framework. Because we are able to resolve the 7.7 ppm proton NMR signal belonging to H1 of BPDC and the 9.5 ppm proton NMR signal belonging to H2′ of BPyDC, we can use a ^{1}H–^{1}H homonuclear correlation NMR experiment for obtaining information about the average H1–H2′ distance. Among several different homonuclear correlation experiments available for the examination of distances between atomic nuclei, we selected the spin-diffusion homonuclear correlation experiment because it enables inspection of relatively long internuclear distances. The ^{1}H spin-diffusion spectrum of ML-DUT-5 in Figure 2, in addition to the expected strong off-diagonal peaks among H1, H2, and the bridging hydroxy H atoms, also shows weak but clear cross-peaks between the H2′ atoms of BPyDC and the H1 atoms of BPDC. The existence of these peaks confirms that polarization transfer between the BPyDC and BPDC linkers can occur in ML-DUT-5, which means that at least some BPyDC and BPDC linkers have to share the same crystallites.

The ^{1}H spin-diffusion experiment can provide an even richer insight into the distribution of the two linkers. The rate of the polarization transfer from BPyDC to BPDC should depend on whether the minority BPyDC linkers are well dispersed throughout the ML-DUT-5 framework or whether they are gathered in domains. In the former case, polarization transfer between the BPyDC and BPDC is expected to be faster than in the latter case in which only a small fraction of BPyDC linkers has BPDC neighbors. For such an insight, the rate of polarization transfer between the BPyDC protons and the BPDC protons should be inspected by variable mixing-time ^{1}H spin-diffusion experiments.

Cross-peak intensities of the variable mixing-time ^{1}H spin-diffusion experiments can be successfully calculated using semi-empirical equations.[9–11] For calculations, only the distances between the protons needs to be known. The equations describing the time dependence of the cross-peak intensities are presented and discussed in the Supporting Information. For the analysis of ML-DUT-5, we built two limiting models, one in which the minority BPyDC linker was homogeneously distributed throughout the framework and another in which the BPyDC linkers were gathered in thin domains. We also built several models between these two limiting cases. We used these models to calculate the ^{1}H spin-diffusion curves. The curves for all the cross-peaks and diagonal peaks for the model with the homogeneous distribution of BPyDC are compared to the experimentally determined curves in Figure 3, and the agreement between the calculated and the measured spin-diffusion curves is excellent. This shows that the semi-empirical description of ^{1}H spin-diffusion can explain the experimental results even in a material as complex as a mixed-linker MOF.

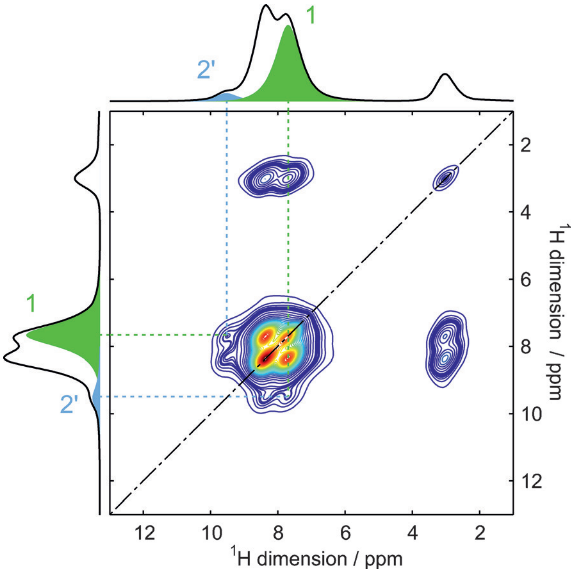


Figure 2. ^{1}H spin-diffusion spectrum of ML-DUT-5. Horizontal and vertical dotted lines mark the frequencies of the H2′ and H1 resonances, and their crossings mark the H2′–H1 cross-peaks. These cross-peaks show that polarization between the BPDC and BPyDC protons can be transferred. Spin-diffusion mixing time was 6.4 ms.

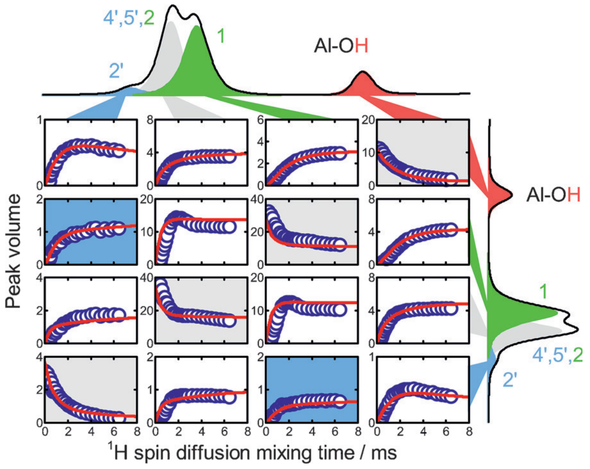


Figure 3. Measured and calculated ^{1}H spin-diffusion curves for ML-DUT-5. The calculated curves were obtained with the model in which BPyDC linkers were homogeneously distributed within the framework. A semi-empirical description seems to be well-suited for the explanation of ^{1}H spin diffusion in MOFs. Two graphs showing the variation of the most important cross-peaks, H2′–H1 and H1–H2′, are shaded in blue.

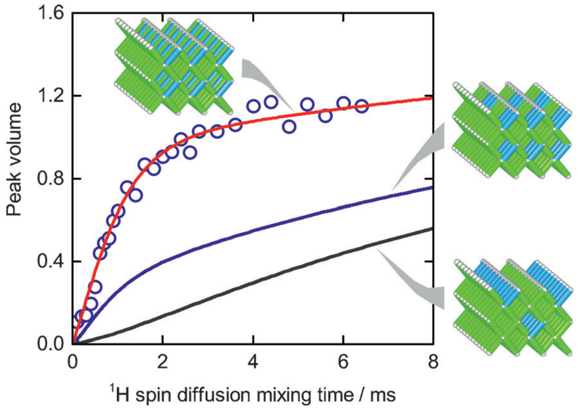


Figure 4. Measured and calculated ^{1}H spin-diffusion curves. Results of calculations for three different models of ML-DUT-5 are presented. The models are characterized by an equal BPDC/BPyDC ratio but different spatial distributions of the two linkers. Only the model with a homogeneously distributed BPyDC linker leads to good agreement with the experimental data.

For the analysis of the distribution of the two linkers within the framework, the most important is the variation of the H2′–H1 cross-peak intensity as this one carries the information on the polarization transfer between BPDC and BPyDC. In Figure 4 we compare the experimentally determined variation with calculations obtained on the basis of three different models, two limiting ones and one in which BPyDC linkers are gathered in very small domains of three molecules. It can be clearly seen in Figure 4 that only the model in which BPyDC linkers are homogeneously distributed within the framework can successfully describe the experimental results. As soon as a BPyDC linker does not have BPDC linkers as nearest neighbors within the layer along the crystallographic *b* axis (along which the distances between the neighboring linkers are the shortest), the predicted polarization transfer between H2′ and H1 becomes much slower than the measured value. These results provide evidence that in our ML-DUT-5 sample BPyDC linkers are homogeneously distributed within the framework and that they do not form domains. Such information about the distribution of BPyDC and BPDC linkers within ML-DUT-5 cannot be obtained by any other approach except the more demanding and much more expensive approach based on the ^{13}C–^{15}N REDOR NMR experiment and ^{15}N isotopically enriched material.

In summary, we have shown that a simple ^{1}H spin-diffusion NMR experiment allows an insight into the distribution of linkers in mixed-linker MOFs. In the case of our ML-DUT-5, the minority linker is well dispersed throughout the framework and does not form single-linker domains. Because ^{1}H nuclei are observed, there are no difficulties with the sensitivity of the experiment, but there can be problems with the resolution. For the approach to be applicable, at least one ^{1}H NMR signal of one linker has to be resolved from at least one ^{1}H NMR signal of another linker. Correct assignment of ^{1}H NMR signals is also crucial. In our case, assignment was supported by the ^{1}H–^{13}C LG-HETCOR experiment and DFT/GIPAW calculation. In fact, the assignment of NMR signals can be more experimentally and computationally demanding than the measurement and modeling of spin-diffusion curves; however, it has to be carried out only once for a given mixed-linker system. Samples obtained in different syntheses or with different ratios of the two linkers can then be inspected quickly using only ^{1}H spin-diffusion experiments. The described approach could be very useful for the inspection of various mixed-linker MOFs.

Keywords: linker distribution · metal–organic frameworks · modeling · NMR spectroscopy · proton spin diffusion

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[1] H. Deng, C. J. Doonan, H. Furukawa, R. B. Ferreira, J. Towne, C. B. Knobler, B. Wang, O. M. Yaghi, *Science* **2010**, *327*, 846–850.
[2] A. F. Gross, E. Sherman, S. L. Mahoney, J. J. Vajo, *J. Phys. Chem. A* **2013**, *117*, 3771–3776.
[3] X. Kong, H. Deng, F. Yan, J. Kim, J. A. Swisher, B. Smit, O. M. Yaghi, J. A. Reimer, *Science* **2013**, *341*, 882–885.
[4] I. Senkovska, F. Hoffmann, M. Fröba, J. Getzschmann, W. Böhlmann, S. Kaskel, *Microporous Mesoporous Mater.* **2009**, *122*, 93–98.
[5] T. Loiseau, C. Serre, C. Huguenard, G. Fink, F. Taulelle, M. Henry, T. Bataille, G. Férey, *Chem. Eur. J.* **2004**, *10*, 1373–1382.
[6] B. J. Van Rossum, C. P. De Groot, V. Ladizhansky, S. Vega, H. J. M. De Groot, *J. Am. Chem. Soc.* **2000**, *122*, 3465–3472.
[7] C. Pickard, F. Mauri, *Phys. Rev. B* **2001**, *63*, 245101.
[8] J. R. Yates, C. J. Pickard, F. Mauri, *Phys. Rev. B* **2007**, *76*, 1–11.
[9] B. Elena, L. Emsley, *J. Am. Chem. Soc.* **2005**, *127*, 9140–9146.
[10] B. Elena, G. Pintacuda, N. Mifsud, L. Emsley, *J. Am. Chem. Soc.* **2006**, *128*, 9555–9560.
[11] E. Salager, R. S. Stein, C. J. Pickard, B. Elena, L. Emsley, *Phys. Chem. Chem. Phys.* **2009**, *11*, 2610–2621.

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