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Fast Wide-line Solid-State NMR on a Low-Cost Benchtop Spectrometer

Morten K. Sørensen,^{*a,b} Nicholas M. Balsgart,^c Ole Jensen,^c Niels Chr. Nielsen,^a and Thomas Vosegaard^a

Abstract: Solid-state NMR may provide access to a wealth of information on molecular structure and dynamics. However, for many applications, the acquisition is challenged by broad resonances implying large spectral linewidths and low sensitivity. Conventionally, this is tackled by using costly and laboratory-fixed spectrometers based on large high-field superconducting magnets. In this Communication, we demonstrate that a range of challenging wide-line solid-state NMR spectra can be acquired on a robust, maintenance-free, low-cost benchtop/mobile NMR spectrometer with a sensitivity comparable to common high-field instruments. The performance and versatility for recording sensitive wide-line spectra is demonstrated through acquisition of ^{31}P NMR of paramagnetic FePO_4 and full quadrupolar lineshapes of Al_2O_3 (^{27}Al) and KNO_3 (^{14}N). Also, we introduce interleaved acquisition of frequency-stepped slices providing a dramatic reduction of the required experiment time.

Solid-state NMR is one of the most powerful techniques for detailed structural, dynamic, and compositional characterization of materials as diverse as catalysts, construction materials, sewage sludge, polymers, salts, electrolytes, minerals, and biological substances.^[1–8] Due to the inherent low sensitivity of NMR, researchers strive for increasing high field strengths, cooled electronics or combination with hyperpolarization to improve this. This implies that currently available and state-of-the-art solid-state NMR instruments becomes excessively expensive, require a large infrastructure, and require operation by experts. Particularly challenging are systems with exceedingly large nuclear spin interactions, requiring the spectra to be acquired with large spectral width, so-called wide-line NMR spectra (or *ultra wide-line* NMR spectra^[9]). The bandwidth of the spectral excitation and detection are limited by the probe and pulse bandwidth. Attempts to overcome this include either i) lowering the quality (Q)-factor of the probe while using small flip angle or long frequency-swept pulses, or ii) acquiring frequency-stepped slices of the spectra. In the first case, sensitivity is sacrificed, since the signal intensity is proportional to $Q^{1/2}$. In the second case, the acquisition becomes demanding in terms of man power, since the probe has to be re-tuned/matched between each acquisition.^[9,10] Several attempts to overcome the latter challenge

have previously been presented, including the use of robotic tune/match assistance or sweeps of the main field rather than the frequency.^[11,12]

In this Communication, we present a complementary route to high-sensitivity acquisition of wide-line NMR spectra using a low-cost and low-field benchtop NMR spectrometer.^[13–15] Using this approach, efficient frequency-stepped acquisition of wide-line NMR spectra may be performed, without tedious sample handling (e.g. packing and spinning a rotor for magic-angle spinning techniques), and utilizing full-automatic tuning (without any requirements for manual tune/match tasks between the slices). The tuning procedure is sufficiently fast that it is possible to introduce interleaved sampling of frequency-stepped slices, which enables a dramatic reduction of the required experiment duration for compounds with long T_1 relaxation time. The use of such equipment may open an entirely new field of wide-line solid-state NMR through enabling the use in both scientific laboratories, industrial production sites, clean-room or fumehood setups, or in field work applications.

For demonstration of the performance of the benchtop solid-state NMR acquisition, we have carried out experiments on three challenging samples. The ^{31}P spectrum of FePO_4 provides an example of a paramagnetic material for which large shifts and line broadening implies that resonances are often considered undetectable in standard NMR experiments.^[16–20] The ^{27}Al (spin $I=5/2$) NMR spectrum of Al_2O_3 and the ^{14}N (spin $I=1$) NMR spectrum of KNO_3 illustrate the acquisition of broad quadrupole lineshapes, where in particular the sensitive acquisition of NMR spectra for integer-spin quadrupolar nuclei is considered particularly challenging.^[21–23] In this context it is relevant to mention that 89 of 120 NMR-active isotopes are quadrupolar spin nuclei, for which NMR studies may be challenged by lineshapes often spanning several MHz^[9,24,25] arguing for a considerable need for frequency-stepped acquisition to achieve non-truncated spectra. For integer-spin nuclei this may be the only route to direct detection of the characteristic quadrupole lineshapes, although it is, in favourable cases, possible to detect the NMR signal from integer-spin quadrupolar nuclei through indirect detection in HMQC experiments.^[26,27]

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Figure 1. Benchtop NMR spectrometer. a) Closed cabinet with touchscreen on the front, handles on the sides for easy transportation, and width-height-depth dimensions indicated, and b) open cabinet with labeling of the visible main components and the top of the inserted sample tube.

Our experiments were conducted using the commercially available Tveskaeg® (NanoNord A/S, Aalborg, Denmark) instrument shown in Figure 1. This instrument is developed mainly for industrial sensor applications like quantification of salt in food and constituents in wastewater, and we have previously published work on quantification of so-called catfines in heavy-fuel oil,^[13] oxygen,^[15] and nutrients in animal slurry^[14] on previous versions of the sensor. We have furthermore exploited the acquisition of low-field MAS NMR with a previous version of the instrument.^[28]

The main elements of the instrument are (i) a 1.5 T (62.4 MHz ^1H frequency) neodymium magnet with magnetic field direction perpendicular to the bore axis, (ii) a broadband probe with automatic continuously adjustable tuning for the entire range of NMR-active isotopes (1 to 67 MHz), 9.2 mm (i.d.) bore diameter, 41 mm coil length, and with preamplifier and transmit/receive switching implemented in the probehead, (iii) a 300 W broadband power amplifier (1–80 MHz, gain 55 dB and flatness ± 1.5 dB), and (iv) a digital Field-Programmable Gate Array (FPGA) console operating at a sampling frequency of 200 MHz, and interfaced from the built-in PC via routines written in MATLAB®. For stabilization of the neodymium magnetic field, all components are gathered in a temperature-controlled cabinet at 42.0 °C. Further experimental details are given in the Supporting Information (SI). Samples are loaded into a tube of perfluoroalkoxy alkane (PFA) with inner diameter 8 mm, and inserted to the probe in the magnet from the top of the cabinet (see Fig. 1). The detection volume is approximately 2 ml, over which the field homogeneity is ca. 500 ppm measured at full-width at half height (FWHH).

Sensitive detection of broadband line shapes are achieved applying Carr-Purcell-Meiboom-Gill (CPMG) echo-train acquisition^[29–31] with averaging of echoes and all echo datapoints weighted based on estimated envelopes (see SI) in combination with the relative large detection volume (ca 25 times larger compared to standard 4 mm rotor corresponding to a sensitivity gain of 5), high Q factor and good filling factor of the probe, optimized sampling (short recycle delays or interleaved slices) and a carefully optimized rf circuit of the NMR instrument.

For the present wide-line acquisition, spectra were constructed point-wise from a frequency-stepped repetition using new tune/match settings for each frequency. Tune/match settings for all frequencies were adjusted prior to acquisition, through an automatic algorithm requiring less than 200 ms. Since the time required to change carrier frequency is very short, it was possible to perform interleaved acquisition with frequency stepping for each scan acquired.

As a first result on our low-field wide-line NMR applications, Figure 2a shows a ^{31}P spectrum acquired for FePO_4 using 80 frequency slices separated by 10 kHz (dots) and a fast recycle delay of 5 ms between scans acquired for each point, leading to an acquisition time of 3 s per point. The spectrum displays a single broad line with a FWHH linewidth of $\Delta\nu = 5000$ ppm, which is an order of magnitude larger than expected based on the magnetic field inhomogeneity of 500 ppm. Due to the CPMG acquisition, the probe- and rf bandwidth will also contribute to the apparent line width, and with the pulses employed here, we expect this factor to be around 1000 ppm, implying this effect cannot fully explain the large linewidth. The slightly asymmetric peak shape in the ^{31}P NMR spectrum suggests the presence of an anisotropic paramagnetic shift (δ_{PM}), which we fit as a regular chemical shift anisotropy (CSA) pattern using SIMPSON.^[32,33] The best fit (Fig. 2b, further details are given in the SI) is obtained using an isotropic chemical shift of $\delta_{\text{iso}} = 6100 \pm 600$ ppm, anisotropic paramagnetic shift of $\delta_{\text{PM}} = 4000 \pm 2000$ ppm, and a Gaussian linebroadening of $\Delta\nu = 5000 \pm 2100$ ppm. These observations agree well with the isotropic shift previously reported in the literature.^[16,17]

Figure 2. a) Experimental ^{31}P spectrum of FePO_4 acquired with 80 frequency points each obtained from CPMG acquisition using 6 echoes with an echo spacing of 90 μs and accumulation of 512 scans with a recycle delay of 5 ms. b) Simulated spectrum (see text).

Figure 3. a) Experimental ^{27}Al spectrum of Al_2O_3 with 100 frequency points each obtained from acquisition of 12 echoes (100 μs echo spacing) and 4 scans per point. b) Simulated spectrum using finite pulses and $C_Q = 2.4$ MHz, $\eta_Q = 0.0$. See SI for further details.

Figure 3a shows the experimental ^{27}Al (spin $I=5/2$) NMR spectrum for a powder sample of Al_2O_3 revealing a first-order quadrupole lineshape. While this compound is not typically considered challenging on a standard NMR setup, we note that significant distortions of the intensities of the satellite transitions may be encountered when using short-pulse excitation of the entire spectral width,^[34] which needs to be taken into considerations in the simulations to obtain the spectral parameters from a powder sample. Using the present approach, the full spectrum presented in Fig. 3a was recorded using 100 frequency steps with 4 scans for each leading to a total duration of 14 minutes (recycle delay 2 s). The fit in Fig. 3b employs the quadrupole coupling parameters known from previous studies ($C_Q = 2.4$ MHz and $\eta_Q = 0.0$)^[34,35] and agree well with experimental spectrum. We note that the singularities and shoulders from *all* satellite transitions are clearly visible in our experimental spectrum and in excellent agreement with the simulation, whereas in Jakobsen et al.^[34] the shoulders of the outermost satellites were not observed due to the limited spectral width (1 MHz). While fast analog/digital converters of today's spectrometers allow much larger spectral widths, the pulse and probe bandwidths may still hamper excitation of satellite transitions with very large frequency offsets.

Figure 4. a) Experimental ^{14}N spectrum of KNO_3 using 80 frequency points each obtained from acquisition of 3072 echoes (300 μs echo spacing) using 20 scans with a recycle delay of 50 s. b) The same experimental spectrum except here acquired using interleaved sampling (~ 2 s between scans) and only 4 scans per point. c) Simulated spectrum using frequency stepping and finite pulses. d) Simulated spectrum assuming ideal single-pulse excitation, ideal detection, and a 20 kHz linebroadening. See SI for further details.

^{14}N has always been considered a big challenge in solid-state NMR, since it has spin $I=1$ and thereby no central transition. With the development of sensitive high-field NMR instruments and with careful experimental setup, direct detection of ^{14}N solid-state NMR spectra is becoming feasible in cases with relatively small quadrupole coupling constants,^[36,37] but a true breakthrough in ^{14}N solid-state NMR is yet to come. To demonstrate the capabilities of low-field wide-line NMR, we have recorded a ^{14}N spectrum of KNO_3 (shown in Fig. 4a) for which previously published spectra have been reported.^[36,38,39] The simulations (Fig. 4c-d) employ the previously reported values of $C_Q = 0.75$ MHz and $\eta_Q = 0.02$ ^[36,39,40] for the quadrupole coupling.

The experiment time using the conventional acquisition procedure was 1361 min (23 h), while the spectrum in Fig. 4b serves to demonstrate the exceptional capabilities of the present low-field approach. This spectrum was accumulated in just 15 min with interleaved sampling. With the same number of scans, the interleaved acquisition method is 18 times faster than conventional sampling for the applied parameters. Most importantly, the 15-min acquisition time is substantially faster than the time spent recording previously published spectra at 7.05 – 14.1 T spectrometers. These experiments were recorded in two hours to four days.^[36,38,39] Although we do not have the data to make a comparison of signal-to-noise ratios, we anticipate that the sensitivity per time in our experiment is at least as good as in the published high-field experiments.^[36,38,39]

The dip at the central part of the spectra (experimental and simulation with finite pulses, Fig. 4a-c) appear since the weak-

pulse approximation^[41] is not valid for those crystallites contributing to the central part of the spectrum, since their effective quadrupole coupling is zero and hence experience a slower nutation frequency. This effect was also observed in the spectrum acquired by Hill and Yesinowski.^[38]

The asymmetry of the spectrum arises due to the frequency-squared dependence on the signal strength (see SI for further details). It is worth noting that this can be observed even in high-field experiments. For example, at 9.4 T it would lead to a 4% difference in the intensities of the “horns”, and may partly explain the asymmetry in the ¹⁴N spectrum of KNO₃ acquired by O'Dell and Schurko at this field strength.^[39]

To conclude, we have demonstrated the use of a low-cost benchtop NMR spectrometer for challenging solid-state NMR experiments including interleaved acquisition of frequency slices. Based on the versatility, high sensitivity, low cost, mobility, and robustness of the method and instrument, we anticipate that this type of spectrometer will open an entirely new field of wide-line solid-state NMR with relevance in food, agricultural, and materials science, and facilitate a much wider use in both scientific laboratories, clean rooms or fumehoods, routine-based applications at industrial production sites, and as a novel sensor in fieldwork applications.

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Entry for the Table of Contents

COMMUNICATION

Solid-state NMR made accessible:

To enable a wider application of solid-state NMR, we present the acquisition of challenging wide-line spectra on a low-cost, mobile, maintenance-free, benchtop NMR instrument. Spectra are obtained fast and with a sensitivity comparable to high-field NMR, including a novel interleaved sample scheme for efficient frequency-stepped acquisition.

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Fast Wide-line Solid-State NMR on a Low-Cost Benchtop Spectrometer