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PERSPECTIVE

Dynamics in the solid-state: perspectives for the investigation of amyloid aggregates, membrane proteins and soluble protein complexes

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Abstract Aggregates formed by amyloidogenic peptides and proteins and reconstituted membrane protein preparations differ significantly in terms of the spectral quality that they display in solid-state NMR experiments. Structural heterogeneity and dynamics can both in principle account for that observation. This perspectives article aims to point out challenges and limitations, but also potential opportunities in the investigation of these systems.

Keywords MAS solid-state NMR · Protein dynamics · Amyloid fibrils · Membrane proteins · Soluble protein complexes

Introduction

The NMR spectral quality for amyloid and membrane protein preparations in the solid-state differs significantly between different systems. Aggregates formed by the Alzheimer's disease Aβ peptide and the *E. coli* multi drug resistance transporter EmrE yield relatively broad resonances (Tycko 2006; Agarwal et al. 2007), whereas others like fibrils formed by the prion protein HET-s and the membrane protein bacteriorhodopsin display very favorable spectral properties (Wasmer et al. 2008; Linser et al. 2011). Obviously, structural heterogeneity can yield inhomogeneous broadening which results in a reduced spectral dispersion. On the other hand, dynamics can have a major impact on the apparent resolution. Structural heterogeneity and dynamics are linked by the activation barrier of a dynamic process. In fact, interconversion of fibril polymorph structures on a timescale of several weeks was shown recently by Tycko and co-workers (Qiang et al. 2013). Macroscopically, these dynamic processes are reflected in chemical exchange between an amyloid fibril-type conformation and a soluble molecule (Carulla et al. 2005; Narayanan et al. 2005; Fawzi et al. 2011). In solution, this exchange process occurs on a timescale of seconds to days. These observations raise the question about the fundamental processes at the atomic level which results in dissociation of a single peptide from the amyloid fibril. Mechanical stress or sonification results in fibril fragmentation. This process generates open ends at which polymerization and de-polymerization can occur. In order to dissociate a single peptide, many hydrogen bonds need to be broken simultaneously. For this to happen, a concerted motion is required. So far, the mechanisms at the atomic level which result in dissociation of aggregated peptides are not very well understood.

For soluble, globular proteins, the protein folding funnel is typically very steep. According to Anfisen's dogma, for a given amino acid sequence only one minimum is populated (Anfinsen 1973). On the other hand, for insoluble

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proteins—in particular for amyloid fibrils—it is generally assumed that this dogma does not hold true, and that amyloids can adopt different conformations, a phenomenon which is referred to as fibril polymorphism. For amyloid fibrils, and maybe for solid-state samples in general, the energy landscape for the "fold" of a particular conformer appears to be characterized by a less distinct profile with more subtle differences between isolated local minima and higher activation barriers. This seems to be a consequence of steric hindrance and higher activation barriers for molecular reorientation due to molecular crowding.

Enzymatic turnover or recognition of ligands is directly coupled to dynamics (Williams et al. 1995; Cole et al. 2002; Henzler-Wildman et al. 2007a, b; Lange et al. 2008). Even though different kinds of functionality rely on dynamics on very different amplitudes and timescales, the critical motility involved in protein functionality seems to occur on a μs timescale. For solid-state preparations, the characteristic time seems to be larger due to the higher molecular weight of the complexes or the anchoring within the lipid matrix. The catalytic rate of rhodopsin in vivo is on the order of 600–1,300 s^{-1} (Heck et al. 2001). ATP synthase is thought to revolve at 650 revolutions per second (Ueno et al. 2005). Similarly, the glucose transporter works with a rate on the order to 300 s^{-1} (Gennis 1989; Stein 1990).

Motion on different timescales can induce deleterious effects on spectral quality: μs-ms time scale motion leads to exchange broadening. ns–μs timescale dynamic processes yield N–H^{α} and N–H^{β} differential relaxation. Standard ^{1}H decoupled solid-state NMR experiments which average H^{α}/H^{β} proton spin states would yield compromised resolution under these circumstances. Solid-state NMR spectroscopy holds a great potential for the study of dynamic processes, as relaxation results from local structural fluctuations only, and is not affected by overall tumbling. This perspectives article aims to highlight how protein dynamics influence the resolution of MAS solid-state NMR resonance line shapes. The hypotheses and speculations made are supplemented with experimental data for a microcrystalline sample of the chicken α-spectrin SH3 domain, the β-barrel membrane protein OmpG, fibrils of the Alzheimer disease β-amyloid peptide, and different assemblies of the 20S proteasome of *Thermoplasma acidophilum*.

Microcrystalline proteins

The highest structural order is expected for a microcrystalline protein preparation. Nevertheless, many residues in the sequence of the α-spectrin SH3 domain show a significant amount of dynamics. Figure 1a represents a selected region of a ^{1}H,^{15}N correlation experiment recorded for a perdeuterated micro-crystalline sample of the α-spectrin SH3 domain, in which exchangeable deuterons are in part back-substituted with protons. Scalar coupling based INEPT experiments (red) and dipolar coupling based CP experiments (black) are superimposed. The N-terminus (e.g., residues T4, G5) is highly flexible and suppressed in the experiments using cross polarization. On the other hand, the resonances of residues located in the N-Src loop (e.g. T37) are exchange broadened and can be observed only in the CP version of the experiment. Typical values for ^{1}H and ^{15}N T_2 relaxation times for the α-spectrin SH3 domain, as well as the experimental line widths are summarized in Table 1.

In the past, we quantified the dynamics of the SH3 domain in the framework of an extended model-free formalism (Chevelkov et al. 2009b). Other groups have worked on the dynamic characterization of ubiquitin (Schanda et al. 2010), superoxide dismutase (Knight et al. 2012) and thioredoxin (Yang et al. 2009). For a quantitative description of motion on two timescales (amplitude and correlation times), at least four linear independent observables are required. We used a combination of ^{15}N–R_1 relaxation rates measured at different field (Chevelkov et al. 2008), ^{1}H–^{15}N dipole–dipole, ^{15}N CSA cross-correlated relaxation, which allows to quantify $J(0)$ spectral density functions related to T_2 type relaxation rates (Chevelkov et al. 2007a, b), as well as dipolar order parameters obtained from CPPI measurements (Chevelkov et al. 2009a). Alternatively, site-specific incoherent T_2 type relaxation rates can be obtained from $T_{1\rho}$ measurements (Akasaka et al. 1983). This approach has been implemented recently for GB1 (Lewandowski et al. 2011b), ubiquitin (Tollinger et al. 2012), and the α-spectrin SH3 domain (Krushelnitsky et al. 2010; Zinkevich et al. 2013).

So far, only model-free motional analyses has been carried out. Obviously, the long-term goal should be to obtain model dependent information on dynamics. The quantification of the asymmetry parameter η of ^{2}H tensors (Hologne et al. 2005, 2006) or of dipolar coupling (Schanda et al. 2011) allows to get information on motional models, such as jump angle and population of side chain rotameric states. Additional information might come from selectively side chain protonated samples in an otherwise deuterated matrix (Asami et al. 2010; Asami and Reif 2013). Availability of an X-ray structure facilitates the analysis of the dynamic behaviour of the protein, since the structure can be employed as a starting point for a molecular dynamics trajectory (Chevelkov et al. 2007c, 2010; Mollica et al. 2012). Such a trajectory is of tremendous help in the interpretation of the NMR data. With the availability of more experimental data, e.g. from RAP labeled samples (Asami et al. 2010), the high degeneracy of data should enable a model-dependent analysis of motion without the need for a MD trajectory.

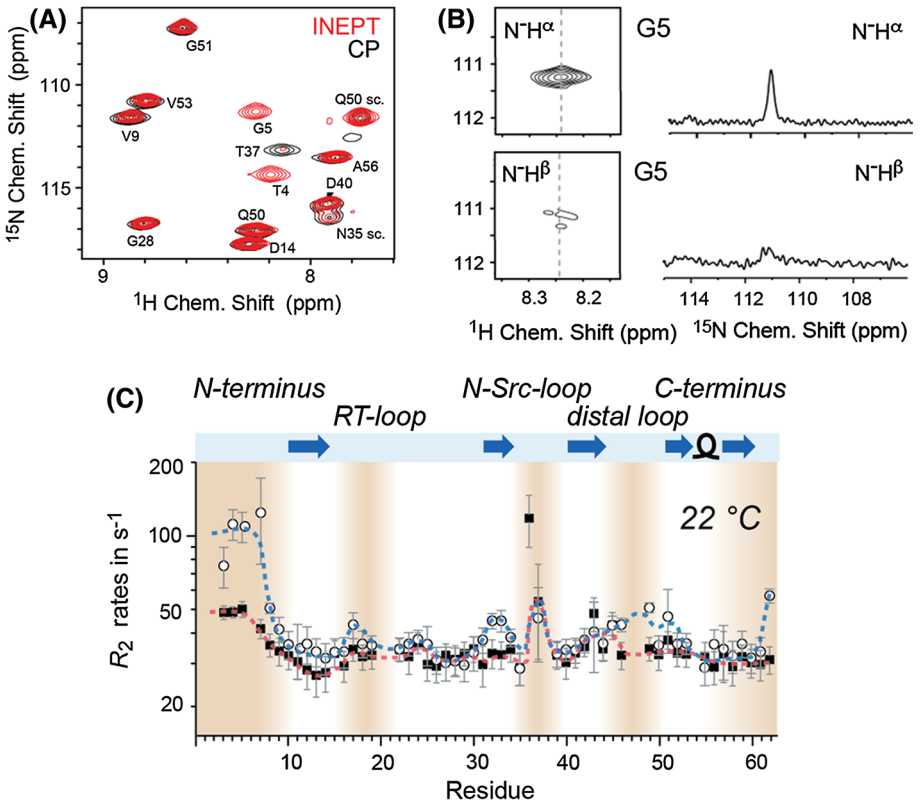

Fig. 1 α-spectrin SH3 $^{1}H,^{15}N$ correlation spectra and relaxation data. **a** Experiments employing scalar (*red*) and dipolar magnetization transfers (*black*) are superimposed. The experiments were recorded on a spectrometer operating at a ^{1}H Larmor frequency of 600 MHz, and at a temperature of 22 °C. The MAS frequency was set to 24 kHz. **b** $N^{-}H^{\alpha}$ and $N^{-}H^{\beta}$ spin-state selective experiments showing the spectral region containing G5. A substantial difference in intensity for the coherences $N^{-}H^{\alpha}$ and $N^{-}H^{\beta}$ are observed, indicating dynamics in the ns–μs regime. Separation of spin-states is achieved by employing the spin-state selective pulse schemes (Linser et al. 2010). **c** Relaxation rates for coherences $N^{-}H^{\alpha}$ (*black squares*) and $N^{-}H^{\beta}$ (*white circles*). Differential relaxation is indicative for large amplitude ns–μs dynamics (Chevelkov et al. 2007a; Skrynnikov 2007). *Dashed lines* are drawn in order to guide the eye. Large differential relaxation rates are found for D62, the N-terminus and the distal loop involving residues 45–50

Table 1 ^{1}H and ^{15}N T_2 relaxation times, theoretical and experimental line widths for a microcrystalline sample of perdeuterated α-spectrin SH3, recrystallized from a buffer containing 75 % D_2O

	$^{1}H^{N}$ T_2 [ms]	^{1}H LW (calc) [Hz]	^{1}H LW (exp) [Hz]	^{15}N T_2 [ms]	^{15}N LW (calc) [Hz]	^{15}N LW (exp) [Hz]
α-spectrin SH3	12.4 ± 0.9	25.7 ± 1.8	25 ± 5	21.8 ± 3.3	14.6 ± 2.2	15 ± 3

T_2 was measured in an echo experiment with one 180° pulse in the center of the incremented delay for the H^{N} bulk signal. The experiments were recorded at a magnetic field strength of 14.1 T and a MAS rotation frequency of 20 kHz and setting the effective temperature to 25 °C

Interestingly, the quantitative dynamic analysis of site-resolved mobility in the α-spectrin SH3 domain shows that the N-terminus is flexible on a high ns timescale (Fig. 1b). We observed temperature dependent transverse relaxation rates for $N–H^{\alpha}$ and $N–H^{\beta}$ differing by up to a factor of 4 for the same amide. Consequently, application of TROSY-type experiments significantly improves the spectral quality of this part of the protein (Linser et al. 2010). This effect is due to substantial cross-correlated relaxation between dipolar and CSA-related relaxation mechanisms (differential relaxation), as shown in Fig. 1c. Use of this effect allows to improve the relaxation properties of the involved nuclei in regions of the protein undergoing high ns timescale motion.

Limits of resolution

In the solid-state, inhomogeneous and homogeneous mechanisms contribute to the NMR line width. Inhomogeneous broadening results in chemical shift dispersion, whereas homogeneous broadening is a consequence of relaxation processes. Obvious factors such as the accuracy of the magic angle, the decoupling performance and the quality of the shim contribute to resonance line width. In

deuterated samples, the spectral quality cannot be improved any further at a certain level of deuteration (Chevelkov et al. 2006; Zhou et al. 2007a, b; Akbey et al. 2010; Lewandowski et al. 2011a), indicating that dipolar interactions are not limiting spectral resolution. Similarly, spinning angle mis-adjustment results in an increase of the line width by a few Hertz (Chevelkov et al. 2007b; Agarwal et al. 2009). The shim contributes less than 1 Hz to proton line width. Back-calculation of the line width from the NMR relaxation data (Chevelkov et al. 2009b) yields a dynamic contribution due to local motion which is on the order of less than 1 Hertz for the majority of all amides (Fig. 1c, the difference rate is proportional to the local correlation time of the motion).

A property which is more difficult to control is the Anisotropic Bulk Magnetic Susceptibility (ABMS) (Alla et al. 1980; Vanderhart et al. 1981; Samoson et al. 2001). ABMS produces a dispersion of chemical shifts, similar to ring current shifts, and is a result of the amorphous arrangement of protein microcrystals in the NMR rotor, potentially interrupted with water and void volume. ABMS cannot be suppressed simply by magic angle spinning. However, since the Hamiltonian for the ABMS interaction has a similar dependence as the isotropic chemical shifts on the nuclear spin part (Samoson et al. 2001), application of a CPMG pulse train can induce significant line narrowing (Garroway 1977; Cowans et al. 1993; Wiench et al. 2008). The spin-echo FID yields a spike spectrum upon Fourier transformation, in which the distance between two spikes is determined by the CPMG frequency. The isotropic chemical shift information can be reconstructed from the spike-spectrum, provided the CPMG frequency is smaller than the frequency difference between two chemical shifts (Cowans et al. 1993). Analogous methods have been found useful applications to enhance sensitivity for ^{29}Si (Wiench et al. 2008; Bocan et al. 2012). However for crowded spectra, it is difficult to implement a CPMG train where the aforementioned condition is satisfied. As an example, Fig. 2a shows that the ^{15}N line width in a deuterated, micro-crystalline sample of the α-spectrin SH3 domain can be reduced from 10 Hz to approximately 6 Hz upon application of a CPMG pulse train. Even though relatively small in absolute numbers, ABMS is thus a major contributor to the residual line width in these samples. A 2D ^{1}H detected ^{15}N/^{1}H correlation experiment (Fig. 2b) was recorded with (black) and without (red) application of CPMG during detection. Due to the cancellation of the ABMS during the CPMG train, the FID lasts much longer and an extended acquisition time was employed ($t^{aq}_{CPMG} = 147$ ms, $t^{aq}_{ref} = 50$ ms). It remains to be seen if and how the isotropic chemical shift information can be extracted from such a spectrum, in cases where the CPMG frequency is higher than the smallest chemical shift differences. We note that CPMG experiments can in principle yield information on chemical exchange processes, and thus on μs–ms dynamics (Lewandowski et al. 2011b; Tollinger et al. 2012). Some care has to be taken to differentiate between chemical exchange processes and refocussing of ABMS.

Amyloid aggregates

In contrast to crystalline proteins, amyloids might be considered as one-dimensional crystals. In that sense, a somewhat lower resolution is expected for amyloids in comparison to microcrystalline samples. For amyloids, however, structural heterogeneity might have a major impact on the experimental spectral properties. For a globular protein, the structure is defined by the amino acid sequence in a unique way (Anfinsen 1973). It is assumed that the same dogma does not apply not amyloids and that amyloid fibrils are not a native fold. Misfolding is rather determined by the chemical properties of the amide backbone (Fandrich et al. 2001). As a consequence, a certain degree of polymorphism is expected in the structure of an amyloid fibril (Petkova et al. 2006; Paravastu et al. 2008). On the other hand, functional amyloids have been discovered to be important elements in bacterial and fungal biofilm formation (Chapman et al. 2002). Fungal prions have been shown to be involved in prion replication (Maddelein et al. 2002). Functional amyloids also play a role in mammalian skin pigmentation (Fowler et al. 2006), and as storage depot for hormones (Maji et al. 2009). This has raised the question whether amyloid fibrils can be considered a functional fold. Riek and Greenwald suggested that an amyloid might even have been the first fold in the early stages of life on earth (Greenwald and Riek 2012). In fact, amino acid sequences that are commonly found in amyloidogenic peptides and proteins occur as well in complex biomolecular machines, such as the nuclear pore complex (Halfmann et al. 2012; Labokha et al. 2013), and are part of the low complexity sequences in RNA binding proteins (Kato et al. 2012; Kim et al. 2013). The fact that an amyloid aggregate can have a function would imply a low structural heterogeneity (at least in certain parts of the protein sequence), and thus a high NMR spectral quality. For the Alzheimer's disease Aβ peptide, which is a key mediator of Alzheimer's disease pathology, such a function in the aggregated state has not been reported yet. Aβ is often thought to be an incidental catabolic by-product that lacks a normal physiological role. However, Aβ has been shown to be a specific ligand for a number of different receptors (Le et al. 2001), transported by complex trafficking pathways (Tanzi et al. 2004), and able to induce pro-inflammatory activities (Halle et al. 2008). Furthermore, Aβ was shown to play a role in activity-dependent regulation of synaptic vesicle release

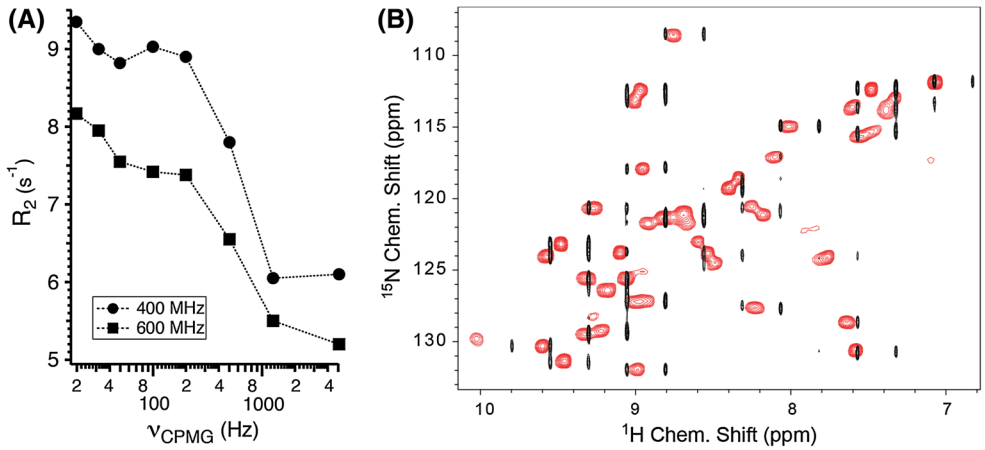

Fig. 2 **a** ^{15}N R_2 relaxation rate upon application of a CPMG pulse train for the bulk amid resonances in α-spectrin SH3. ν_{CPMG} is defined as $1/(\tau - 180 - \tau)$. The decay in the relaxation rates is due to the refocussing of ABMS. **b** N/H correlation with a CPMG pulse train applied during acquisition (*black*), superimposed with a regular N/H correlation (*red*) for α-spectrin SH3. In the CPMG experiment, $\tau = 5$ ms was employed. The acquisition time was set to 147 ms, whereas the signal was acquired for only 50 ms in the N/H reference experiment. Both spectra were recorded at a spectrometer operating at 400 MHz. In the CPMG experiment, resonances appear significantly more narrow. However, application of the CPMG refocussing pulses results in undefined isotropic shifts

(Abramov et al. 2009), and suggested to have antimicrobial activity (Soscia et al. 2010).

Amyloid assemblies have been reported to be dynamic assemblies. Dobson and co-workers demonstrated that SH3 molecules constantly dissociate from and re-associate with PI(3)K-SH3 fibrils (Carulla et al. 2005). ESI–MS H/D exchange studies yielded two distinct populations for the fibrillar assembly after exposure of the fibrils to exchange, corresponding to a population of fast-exchanging and slow-exchanging molecules. Fit of the MS data to a model in which monomers can be added to the fibril ends yields a recycling time on the order of 2–20 days, depending on the length of the fibril (Carulla et al. 2005). By contrast, Clore and co-workers found faster exchange rates in case of the Alzheimer's disease peptide Aβ40 and Aβ42 (Fawzi et al. 2010, 2011). Quantitative fit of ^{15}N DEST (Dark-state Exchange Saturation Transfer) data yield dissociation rates which are on the order of $k_{off} = 50$–100 s^{-1}, depending on concentration and temperature. Exchange between an aggregated and a soluble form of the Aβ40 was also observed by STD-NMR experiments (Narayanan et al. 2005). Recently, this interconversion could be shown directly by solid-state NMR experiments (Qiang et al. 2013). Tycko and co-workers have shown that an isolated fibril polymorph structure can convert into another polymorph on a timescale of several weeks. Dynamics in a C-terminally truncated variant of the human prion protein (HuPrP23-144) has been probed in $T_{1\rho}$ type experiments (Helmus et al. 2008, 2010). It is found that the rigid core residue in the prion fibrils undergoes μs-ms timescale motion. It will be interesting to see how this dynamics compares to the exchange dynamics observed e.g. in DEST experiments.

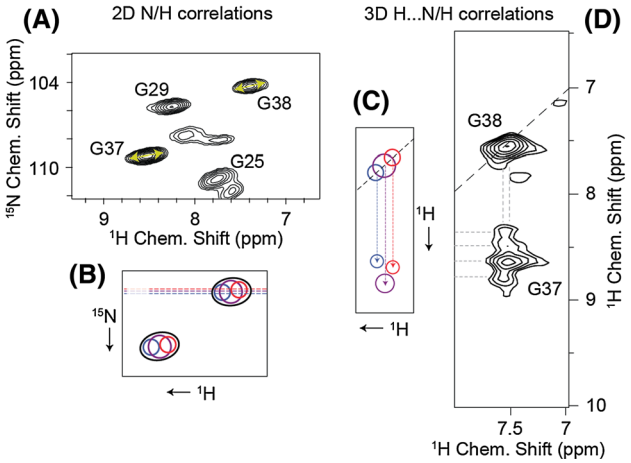

Fig. 3 MAS solid-state NMR experiments for a fibril sample of the perdeuterated Alzheimer's disease peptide $A\beta^{1-40}$. Exchangeable sites are back-substituted with 20 % protons. **a** 2D N/H-correlation spectrum (selected region) (Linser et al., 2011). **b/c** Schematic representation of a 2D N/H and 3D ^{15}N edited H/H correlation spectrum using RFDR for homonuclear mixing. The different colors indicate three different fibril conformers. **d** Experimental ^{15}N edited H/H correlation spectrum focussing on the cross peak between the amide protons of residues G37 and G38 in $A\beta^{1-40}$

The broad proton lines observed previously in proton detected experiments (Fig. 3) recorded for fibrils of per-deuterated Alzheimer's disease Aβ40 (Linser et al. 2011; Agarwal et al. 2013) raise the question about the origin of line width in these kind of samples. For fibrils of α-synuclein fibrils (Zhou et al. 2012) and hydrophobins (Morris et al. 2012), which are functional amyloids affecting surface properties of fungal spores, a similar spectral quality is obtained. These common observations might indicate that

Table 2 ^{1}H, ^{15}N T_2 relaxation times, theoretical and experimental line widths for a fibril sample of perdeuterated Aβ^{1-40}

	$^{1}H^{N}$ T_2 [ms]	^{1}H LW (calc) [Hz]	^{1}H LW (exp) [Hz]	^{15}N T_2 [ms]	^{15}N LW (calc) [Hz]	^{15}N LW (exp) [Hz]
Aβ^{1-40}	8.2 ± 0.2	38.8 ± 1.0	170 ± 47	13.5 ± 0.2	23.6 ± 0.3	38 ± 10

All experimental parameters as magnetic field strength, MAS rotation frequency and temperature were the same as described above for the microcrystalline SH3 sample

the observed broad amide resonances could be a general phenomenon.

Interestingly, heteronuclear detected experiments of a protonated fibril sample (Lopez del Amo et al. 2012a, b) display a reasonable resolution which seems to be limited by evolution of scalar couplings (ca. 100–130 Hz in the ^{13}C dimension, 38 ± 10 Hz for ^{15}N). For preparation of protonated and deuterated fibrils samples, the same seeds have been employed. In the deuterated fibril preparation, the line width of protons is significantly larger in comparison to the line width of nitrogens (170 ± 47 Hz for ^{1}H, and 38 ± 10 Hz for ^{15}N, Table 2). This is surprising as the effective spectral frequency range (in Hz) for the proton and nitrogen dimension is comparable (3 vs. 30 ppm). Therefore, a similar sensitivity with respect to conformational changes would be expected for both nuclei. For protons, however, a fourfold reduced resolution is observed.

Comparison of the ^{1}H line width and the T_2 decay time measured in a spin-echo experiment (Table 2) shows that the proton resonance lines are inhomogeneously broadened, which is presumably due to a superposition of resonances from multiple fibril polymorphs. Similarly, the skew, asymmetric peak shapes in Fig. 3a seem to indicate superposition of multiple resonances reflecting a certain degree of conformational heterogeneity. Higher dimensional experiments might allow to resolve contributions from different polymorphs. A schematic representation of the expected signal pattern is shown in Fig. 3c. In fact, multiple cross peaks are observed for the correlation H^{N}(G38)–H^{N}(G37) in an ^{15}N-edited homonuclear H/H NOESY-type experiment (Fig. 3d). In the future, experiments of that kind might allow a site-specific characterization of conformational heterogeneity in an amyloid fibril.

In order to find out whether line broadening originates from ns–μs timescale motion, we recorded TROSY-type experiments in the solid-state (Fig. 4). Similar as above for the micro-crystalline preparation of the α-spectrin SH3 domain (Fig. 1b), differential broadening of the ^{15}N–H^{α} (red) and ^{15}N–H^{β} spin-states would be expected, in case motionally induced relaxation contributes significantly to the resonance line width. However, no significant differences for the intensities of the two spin states are observed, indicating that no large amplitude ns-μs timescale motion occurs. Increase of the exchange dynamics would potentially result in more narrow resonance lines.

The variation of ^{1}H and ^{15}N shifts seem to be concerted yielding to oval-shaped, tilted peaks (Fig. 3a). The tilt is very similar for most peaks with a characteristic slope of roughly 13 ± 0.7 (Hz,^{1}H)/(Hz,^{15}N). The effect of pressure might explain the observed N/H peak shapes in part. It is known that pressure has a significant impact on NMR chemical shifts, in particular for exchangeable protons (Arnold et al. 2002; Kitahara et al. 2013).

The pressure acting on a sample in a volume element at a distance r_0 from the rotor axis can be approximated by Pascal's law (Fig. 5). r_0 refers to the inner radius of the MAS rotor, ρ describes the density of the protein and ν_R represents the MAS rotation frequency. The protein density can be assumed to be 1.4 g/cm^{-3} (Quillin et al. 2000). According to this formula, the maximum pressure for a rotating sample in a 3.2 mm MAS rotor (r_0 = 1.2 mm, ν_R = 20 kHz) is on the order of 320 bar (32 MPa). It was found that the pressure induced proton chemical shift change is in the range of 0.4 ppm GPa^{-1} (Arnold et al. 2002). This yields a theoretical proton chemical shift distribution of about 10 Hz for a spectrometer operating at 14.1 T (600 MHz), assuming a homogeneous distribution of the sample in the rotor. In reality, the pressure gradient is presumably smaller, as the sample sediments on the walls of the rotor, with not much protein being localized close to the rotor axis. Pressure induced ^{15}N chemical shift changes $\Delta\delta_P$ are on the order of 1.5–2.5 ppm GPa^{-1}. Interestingly, reduced local compressibilities are observed for β-sheets with $\Delta\delta_{P,N}$ = 1.5 ppm GPa^{-1} (Akasaka et al. 1999). For ^{15}N, therefore a distribution of resonances within 3 Hz would be expected. Overall, the expected differences appear to be rather small, and it seems that pressure does not contribute significantly to the experimental (proton) line width. In addition to chemical shift changes from isotropic compression, pressure induced mechanical deformations of the investigated sample could be responsible for the observed resonance line broadening. Due to their shape, amyloid fibrils appear to be more prone to deformation in comparison to microcrystalline protein preparations. This might be another factor, which might result in larger broadenings for amyloid fibrils in comparison to crystalline samples.

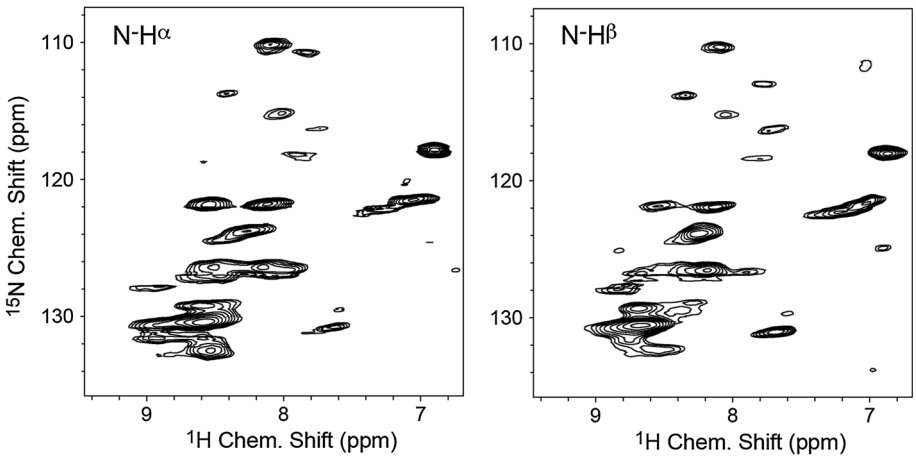

Fig. 4 Comparison of 2D N/H correlation spectra selecting the $^{15}N^{-}H^{\alpha}$ (*left*) and $^{15}N^{-}H^{\beta}$ (*right*) spin-states in a deuterated Aβ(1-40) fibril sample. No significant differences are observed, indicating that no large amplitude ns–μs timescale motion occurs (Linser et al. 2010). The experiments were recorded at 900 MHz within 3 h, employing $t_1^{max} = 30$ ms. The MAS rotation frequency was adjusted to 20 kHz. The effective sample temperature was set to 20 °C

$$p(r) = \int_0^{r_0} dr\ \rho\ a(r) = \rho \int_0^{r_0} dr 4\pi^2 \nu_R^2\ r$$
$$= 2\pi^2 \nu_R^2\ \rho\ r_0^2$$

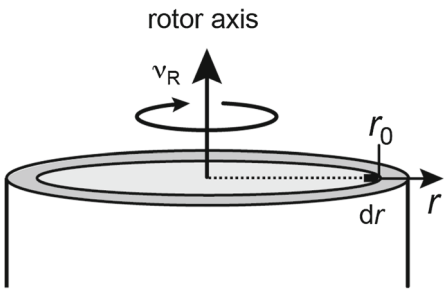

Fig. 5 Pressure acting on a rotating sample under magic angle spinning

Taken together, the line width in our Aβ40 fibril preparations is determined by structural heterogeneity and/or by dynamics on a μs–ms timescale. Measurements carried out at increased temperature in principle would allow one to get into the fast-exchange limit. Currently, the experimentally available temperature range is limited as sealing of NMR rotors is difficult to prevent solvent evaporation and dehydration over time.

Membrane proteins

Using solid-state NMR methodology, the first structures of membrane proteins containing multiple membrane spanning helices have been determined using solid-state NMR methodology (Park et al. 2012; Shahid et al. 2012; Wang et al. 2013a). In these cases, the resolution in $^{13}C/^{13}C$ and $^{13}C/^{15}N$ correlation experiments is excellent. Other systems display a much less favorable spectral dispersion (Agarwal et al., 2007). In addition to the crystallization process itself, Reconstitution of a membrane protein into the correct lipid environment is obviously an issue, and use of the *wrong* lipids might result in heterogeneity or exchange broadening. Collection of cell wall fragments which contain the over-expressed membrane protein, that are packed directly into a MAS rotor without any further purification and reconstitution might be a solution to that issue (Renault et al. 2011; Jacso et al. 2012; Takahashi et al. 2013; Wang et al. 2013b). This approach, however, suffers typically from low sensitivity. Dynamic Nuclear Polarization (DNP) is needed to regain the sensitivity necessary to acquire multidimensional NMR experiments (Hall et al. 1997). At least for certain samples, the decrease in resolution due to sample freezing can be overcome by going to higher-field instrumentation (Lopez del Amo et al. 2013). In standard solid-state NMR experiments performed at room temperature, sample heating due to high-power RF irradiation during proton acquisition can compromise sample integrity (Linser et al. 2007).

For a long time, crystallization of G protein coupled receptors (GPCRs) was hampered due to their large intrinsic dynamics which prevented the growth of well diffracting protein crystals. Directed mutagensis (Sarkar et al. 2008; Chen et al. 2012; Schlinkmann et al. 2012),

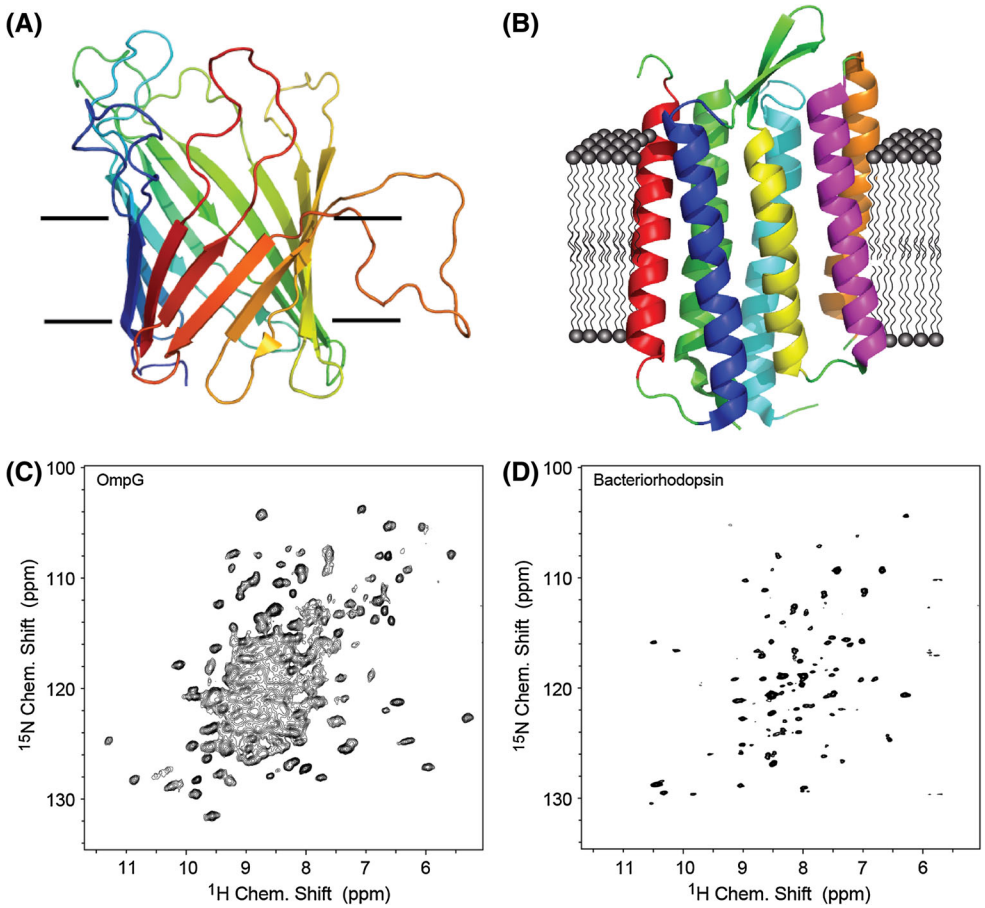

Fig. 6 Structural model of OmpG (PDB ID: 2JQY) (**a**), and Bacteriorhodopsin (bR, PDB ID: 1C3W) (**b**). The respective ^{1}H,^{15}N correlation spectra are shown in (**c**) and (**d**). bR was prepared from native purple membranes (Patzelt et al. 1997), whereas OmpG was reconstituted in *E.coli* lipid extract (Hiller et al. 2005). Figure reproduced with permission from Wiley (Linser et al. 2011)

binding of antibodies (Rasmussen et al. 2007), or GPCR engineering (Rosenbaum et al. 2007) was needed to suppress this motional flexibility. In fact, membrane proteins are not tightly packed, but contain a considerable number of internal cavities that differ in volume, polarity and solvent accessibility as well as in their filling with internal water (Rose et al. 2013). These cavities are supposed to be regions of high physical compressibility. In that sense, a large degree of conformational flexibility is expected and needed to facilitate transitions between different functional states.

In comparison to ^{13}C or ^{15}N, protons seem to be a more sensitive probes to detect either structural heterogeneity and/or dynamics. Figure 6 shows 2D N/H correlation spectra of OmpG and bacteriorhodopsin (bR) (Linser et al. 2011). For both preparations, the labeling pattern as described above for the α-spectrin SH3 domain has been employed (perdeuterated at non-exchangeable sites, and 10–30 % protonation at exchangeable positions). Acquisition and processing parameters are comparable for the experiments described here and above. Obviously, the spectral quality for these two preparations is very different. Values for the ^{1}H and ^{15}N T_2 decay time from spin-echo experiments, as well as the calculated and experimental line width are summarized in Table 3. Other deuterated protein preparations in the solid-state such as the 20 kDa membrane protein DsbB reconstituted in *E. coli* lipids (Zhou et al. 2012) and the DMPC/DMPA reconstituted proteorhodopsin (Ward et al. 2011) yield a ^{1}H,^{15}N spectral resolution which is comparable to the OmpG preparation.

For OmpG, signal intensities for dipolar-transfer based experiments drastically increase at lower temperatures (3 °C). However, also at room temperature dipolar transfers are possible. This is in contrast to the observed broadening of resonances in the flexible N- and C-terminus in the SH3 domain of α-spectrin, for which only scalar transfers give rise to detectable signal. This indicates that the amplitude of motion in OmpG must be much smaller. Comparing TROSY/anti-TROSY 2D N/H experiments (without and with additional relaxation delays to enhance differences) does not indicate a large amount of differential relaxation (data not shown), suggesting that ns-µs

Table 3 ^{1}H, ^{15}N T_2 relaxation times, theoretical and experimental line widths for perdeuterated samples of the outer membrane β-barrel protein OmpG and bacteriorhodopsin (bR)

	$^{1}H^{N}$ T_2 [ms]	^{1}H LW (calc) [Hz]	^{1}H LW (exp) [Hz]	^{15}N T_2 [ms]	^{15}N LW (calc) [Hz]	^{15}N LW (exp) [Hz]
OmpG in						
Protonated lipids	6.8 ± 0.5	46.8 ± 3.4	121 ± 42	10.0 ± 1.0	31.8 ± 3.2	60 ± 34
Deuterated lipids	9.2 ± 1.0	34.6 ± 3.8	101 ± 31	11.1 ± 2.3	28.7 ± 6.2	53 ± 23
Bacteriorhodopsin (bR)	n.d.	–	27 ± 7	n.d.	–	11 ± 3

All experimental parameters were the same as described above for the microcrystalline SH3 sample

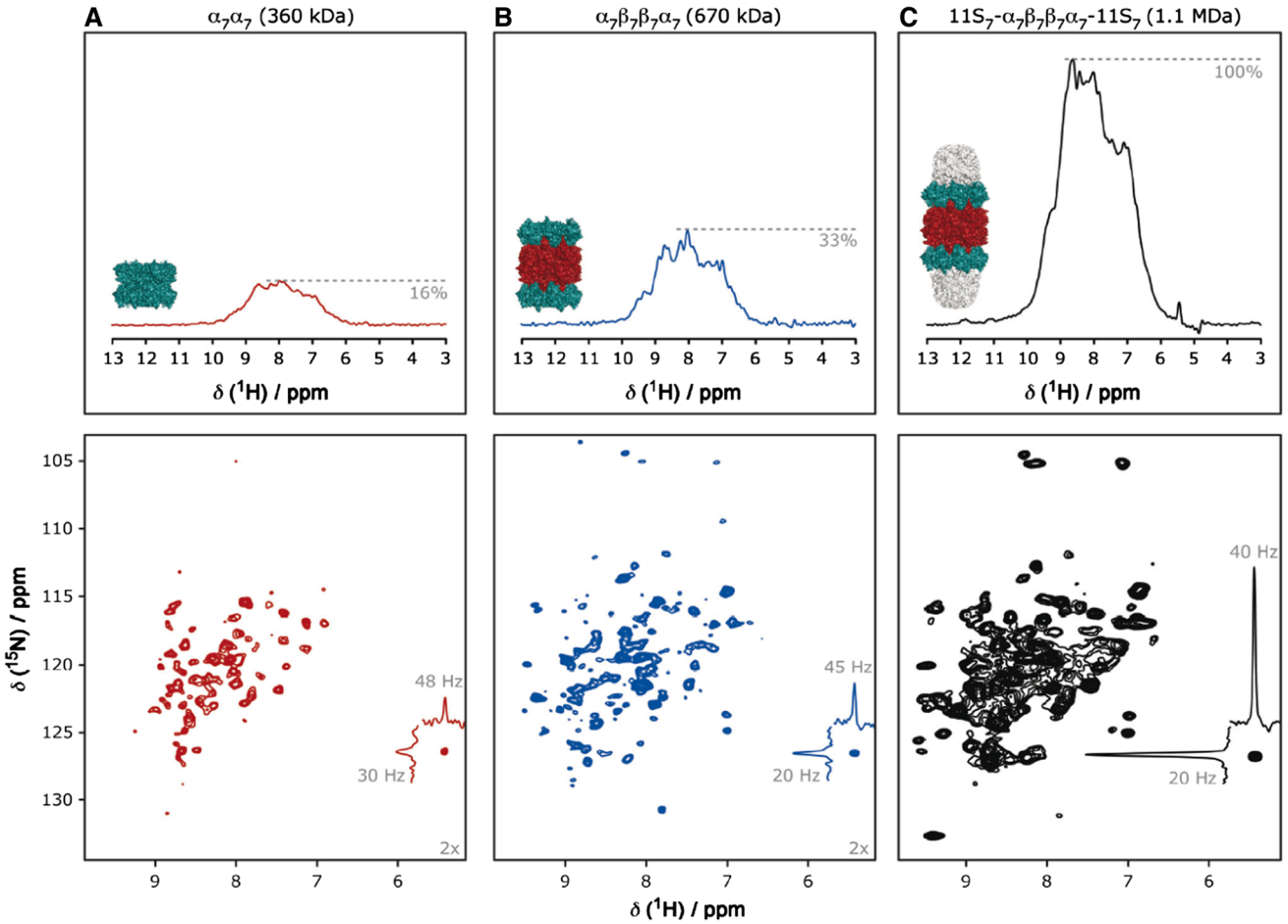

Fig. 7 Proton-detected MAS experiments and the effect of increasing molecular weight for different assemblies of the 20S proteasome of *Thermoplasma acidophilum*. Cross polarization (CP) based 2D ^{1}H-^{15}N correlation spectra are shown on the bottom, the corresponding 1D versions are represented on the top for the 360 kDa $\alpha_7\alpha_7$ (**a**), the 670 kDa $\alpha_7\beta_7\beta_7\alpha_7$ (**b**) and the 1.1 MDa 11S-$\alpha_7\beta_7\beta_7\alpha_7$-11S complex (**c**). The spectra were recorded at 0 °C and with 22 kHz MAS. Acquisition and processing parameters were identical. The signal intensities of ^{15}N-filtered ^{1}H-1D spectra are normalized to account for the different concentrations of the α-subunit. The calculated fraction of sedimented protein amounts to 97.7, 98.8 and 99.7 % for $\alpha_7\alpha_7$, $\alpha_7\beta_7\beta_7\alpha_7$ and 11S-$\alpha_7\beta_7\beta_7\alpha_7$-11S, respectively. Figure reproduced with permission from Wiley (Mainz et al. 2013)

dynamics do not significantly influence resonance line width for OmpG. On the other hand, membrane proteins undergo μs timescale rotational diffusion within the lipid bilayer (Saffman et al. 1975; Austin et al. 1979; Cherry 1979, 2005). This motion is as well detected in solid-state NMR experiments (Park et al. 2006). For the transmembrane helix of the channel-forming domain of the protein Vpu from HIV-1 in in DOPC/DOPG bilayers, a characteristic rotational diffusion time on the order of 10 μs was found. In aligned phospholipid bilayers, this motion is exploited to yield better resolved PISEMA spectra (Lu et al. 2012). In non-aligned, amorphous

samples the uniaxial rotation of membrane proteins is employed to determine the relative orientation of a membrane helix with respect to the phospholipid bilayer (Hong et al. 2006; Cady et al. 2007). On the other hand, local motion in sensory rhodopsin was shown to occur on a μs timescale (Good et al. 2014). It will be interesting to see how these two types of motion can possibly be separated.

The resolution in DMPC/DMPA reconstituted proteorhodopsin (Ward et al. 2011) is lower in comparison to bR in native purple membranes (Linser et al. 2011). bR is found to be a trimer in the lipid bilayer (Luecke et al. 1999; Sapra et al. 2006). It thus seems that protein–protein interactions inbetween bR molecules stabilize the membrane structure and prevent rotational diffusion. DOPC reconstituted proteorhodopsin shows a hexameric arrangement of proteorhodopsin molecules (Klyszejko et al. 2008). It is thus conceivable that interdigitation of protomers from different oligomers can affect rotational diffusion in the lipid bilayer. Ladizhansky and co-worker employed DMPC/DMPA to reconstitute proteorhodopsin (Ward et al. 2011). Choice of lipids and crystallization conditions will have an effect on the architecture of the oligomeric state of proteorhodopsin, and it remains to be seen what the exact reason for the observed differences in spectral quality is.

Soluble protein complexes

In magic-angle spinning (MAS) solid-state NMR, immobilized samples are spun rapidly in a cylindrical rotor, which is inclined at an angle Θ_{MA} of 54.74° relative to the magnetic field of the NMR spectrometer (Andrew et al. 1958). Line narrowing by MAS is achieved if the correlation time of the investigated molecules is much larger than the rotor period. This is obviously the case for an immobilized solid sample. However, this also holds true for a solution of a high molecular weight protein at low temperature and high viscosity (Mainz et al. 2009, 2012). Bertini et al. have suggested that strong centrifugal forces during MAS lead to reversible protein sedimentation (Bertini et al. 2011) which effectively induces immobilization of the protein. In fact, the tumbling correlation times of protein complexes such as αB-crystallin with a molecular weight of ca. 600 kDa amount only to a few μs in the absence of MAS (Ravera et al. 2013). It might be argued that biological solid-state samples such as fibrils or membrane proteins are always prepared by sedimentation (Gardiennet et al. 2012). Nevertheless, it is remarkable that this approach allows to overcome the molecular weight limit imposed by tumbling in classical solution-state NMR. Mega-Dalton protein complexes are now accessible which previously could only be investigated in selectively methyl labeled samples in solution-state NMR (Mainz et al. 2013).

Figure 7 shows ^{15}N filtered 1D spectra acquired for different 20S proteasome complexes from *Thermoplasma acidophilum*. Interestingly, the intensity of the respective spectra increases by more than a factor of 7 when the molecular weight of the complex is increased from 360 kDa to 1.1 MDa. This is unexpected, as the calculated fraction of sedimented protein amounts to 97.7, 98.8 and 99.7 % for $\alpha_7\alpha_7$, $\alpha_7\beta_7\beta_7\alpha_7$ and 11S-$\alpha_7\beta_7\beta_7\alpha_7$-11S, respectively (Ferella et al. 2013), and indicates that there is still residual mobility in the sediment, which presumably induces exchange broadening.

On the other hand, this approach allows to circumvent sample preparation issues. Selection of the right precipitation conditions is not anymore necessary. For ligand binding studies, crystallization with and without ligand can yield different crystal forms that result in different spectral patterns. This complicates the analysis of chemical shift perturbations. In particular for weakly interacting systems, such as misfolding peptides and proteins binding to molecular chaperones, this approach might be an interesting alternative to crystallization, as the two components are very much different in terms of their solubility and co-precipitates are thus difficult to obtain.

Conclusion

Taken together, we have shown how dilution of the proton spin network can facilitate MAS solid-state NMR experiments. In microcrystalline protein samples, residual line width is not determined by the efficiency of heteronuclear dipolar decoupling, but by the anisotropic bulk magnetic susceptibility (ABMS). In amyloid aggregates and membrane proteins, additional contributions to line width originate from structural heterogeneity. We have investigated the effect of pressure on amide chemical shifts. We estimate the contribution to line width by MAS induced pressure to be on the order of 10 and 3 Hz for ^{1}H and ^{15}N, respectively. The dilute proton network allows an artifact-free analysis of dynamics in the solid-state. In contrast to micro-crystalline protein preparations where many residues undergo ns–μs motion, it seems that amyloid aggregates and membrane proteins predominantly display μs–ms dynamics. It will be exciting to see in the future how all experimental observables will be integrated to yield a model-dependent analysis of motional processes. At the same time, choice of lipids, temperature and other solution conditions can affect the achievable resolution, and it remains to be seen how this can be exploited to learn more about the functioning of membrane proteins and amyloid dynamics and propagation.

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