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## Experimental constraints on quaternary structure in Alzheimer's $\beta$ -amyloid fibrils<sup>†</sup>

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### Abstract

We describe solid state nuclear magnetic resonance (NMR) measurements on fibrils formed by the 40-residue  $\beta$ -amyloid peptide associated with Alzheimer's disease ( $A\beta_{1-40}$ ) that place constraints on the identity and symmetry of contacts between in-register, parallel  $\beta$ -sheets in the fibrils. We refer to these contacts as internal and external quaternary contacts, depending on whether they are within a single molecular layer or between molecular layers. The data include: (1) two-dimensional  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectra that indicate internal quaternary contacts between sidechains of L17 and F19 and sidechains of I32, L34, and V36, as well as external quaternary contacts between sidechains of I31 and G37; (2) two-dimensional  $^{15}\text{N}$ - $^{13}\text{C}$  NMR spectra that indicate external quaternary contacts between the sidechain of M35 and the peptide backbone at G33; (3) measurements of magnetic dipole-dipole couplings between the sidechain carboxylate group of D23 and the sidechain amine group of K28 that indicate salt bridge interactions. Isotopic dilution experiments allow us to make distinctions between intramolecular and intermolecular contacts. Based on these data and previously-determined structural constraints from solid state NMR and electron microscopy, we construct full molecular models using restrained molecular dynamics simulations and restrained energy minimization. These models apply to  $A\beta_{1-40}$  fibrils grown with gentle agitation. We also present evidence for different internal quaternary contacts in  $A\beta_{1-40}$  fibrils grown without agitation.

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Amyloid fibrils are filamentous aggregates formed by a wide variety of peptides and proteins and distinguished from other types of protein fibrils by their appearance in electron microscope (EM) images, by their dye-binding properties, and by the presence of cross- $\beta$  structural motifs within the fibrils (1,2). Amyloid fibrils are likely causative or contributing agents in diseases such as Alzheimer's disease, type 2 diabetes, Parkinson's disease, and transmissible spongiform encephalopathies (3). The formation and transmission of several prions in yeast and fungi is known to be based on the formation of amyloid fibrils by particular proteins (4). Many proteins that are not known to form amyloid fibrils *in vivo* can also form amyloid fibrils *in vitro* under conditions that destabilize their unaggregated states (5,6).

Determination of the full molecular structures of amyloid fibrils requires unusual experimental approaches, due to their inherent noncrystalline, insoluble nature (2). Full structure determination requires experimental constraints at the primary, secondary, tertiary, and quaternary structural levels (7). As for monomeric peptides and proteins, primary and secondary structures refer to the amino acid sequence and to segments with standard backbone

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conformations, respectively. In the case of amyloid fibrils,  $\beta$ -strands are the predominant secondary structural elements. Helical segments have not yet been detected in the core structures of amyloid fibrils. Experimental determination of secondary structure in amyloid fibrils therefore consists of the identification of structurally ordered and disordered segments, and the identification of  $\beta$ -strand and non- $\beta$ -strand segments (*i.e.*, loops, bends, or turns). Solid state nuclear magnetic resonance (NMR) (8-19), hydrogen/deuterium (H/D) exchange (14, 20-27), proline-scanning mutagenesis (28,29), electron paramagnetic resonance (EPR) (30-32), and infrared and Raman spectroscopies (33,34) have been applied to the problem of secondary structure determination. Tertiary structure in amyloid fibrils can be defined as the organization of  $\beta$ -strand segments into parallel or antiparallel  $\beta$ -sheets, with a specific registry of inter-strand hydrogen bonds within the  $\beta$ -sheets. Solid state NMR (7,8,11,15,16,19,35-44) and EPR (30-32,45,46) measurements have been particularly useful in experimental determinations of tertiary structure.

Quaternary structure in amyloid fibrils can then be defined as the positions and orientations of  $\beta$ -sheets relative to one another. As demonstrated by x-ray fiber diffraction (1,33,47,48), EM (49), and solid state NMR (50) data, the  $\beta$ -sheets in amyloid fibrils have a "cross- $\beta$ " orientation, meaning that the  $\beta$ -strand segments run approximately perpendicular to the long axes of the fibrils, while the inter-strand hydrogen bonds are directed approximately parallel to the long axes. As represented in recent models for amyloid structures (7,10,14,29,36,42,44,51-59) and supported by recent x-ray crystal structures of short amyloid-forming peptides (60), the core of an amyloid fibril contains two or more layers of  $\beta$ -sheets. The quaternary structure is dictated by a set of contacts among amino acid sidechains that project from adjacent  $\beta$ -sheets. In fibrils formed by relatively long peptides (or by *bona fide* proteins), the adjacent  $\beta$ -sheets may be formed either by  $\beta$ -strands from the same peptide molecules or by  $\beta$ -strands from different molecules. Thus, the sidechain contacts that dictate quaternary structure may be either intramolecular or intermolecular.

In the case of fibrils formed by the 40-residue  $\beta$ -amyloid peptide associated with Alzheimer's disease ( $A\beta_{1-40}$ ), solid state  $^{13}\text{C}$  NMR chemical shifts and linewidths indicate that residues 1-9 are structurally disordered, residues 10-22 and 30-40 form  $\beta$ -strands (with enhanced disorder at the C-terminus and in the vicinity of residues 14-16 for fibrils grown with gentle agitation), and residues 23-29 form a bend or loop (10,11). The two  $\beta$ -strands form two separate registers, parallel  $\beta$ -sheets (37,38), which can make contact with one another because of the intervening bend segment (9). This description of secondary and tertiary structure in  $A\beta_{1-40}$  fibrils is generally consistent with EPR (32), proline-scanning mutagenesis (29), proteolysis (61,62), and hydrogen exchange (20,27) data. Secondary and tertiary structural differences between models derived from solid state NMR data (7,10) and from other data (29,52) are largely attributable to differences in the information content of the various techniques and their sensitivity to structural disorder, as discussed below.

Experimental determination of quaternary structure in amyloid fibrils has been comparatively difficult. In most models, quaternary contacts and quaternary structure have been chosen in the absence of direct experimental constraints. In the case of  $A\beta_{1-40}$  fibrils, information about quaternary contacts was obtained recently by Shivaprasad *et al.* (52), who performed disulfide crosslinking experiments on double cysteine mutants of  $A\beta_{1-40}$ . Fibrils formed by the L17C/L34C mutant (initially in the reduced state) were oxidatively crosslinked most rapidly and efficiently, suggesting a quaternary structure in which sidechains of L17 and L34 are in proximity. L17C/L34C, L17C/M35C, and L17C/V36C mutants were all found to be capable of forming amyloid fibrils after oxidation in their monomeric states, suggesting that other quaternary structures for  $A\beta_{1-40}$  fibrils are also possible (52). This result is consistent with the molecular-level polymorphism of  $A\beta_{1-40}$  fibrils revealed by our own recent solid state NMR and EM experiments (11).

In related work, Sciarretta *et al.* have shown that A $\beta$ <sub>1-40</sub> with a lactam crosslink between D23 and K28 forms amyloid fibrils significantly more rapidly than the wild type peptide, with no detectable lag phase in the fibrillization kinetics (43). The lactam crosslinking experiments are consistent with the observation by solid state NMR of a salt bridge interaction between sidechains of D23 and K28 in fibrils formed with gentle agitation (10,11). The absence of this salt bridge in fibrils formed under purely quiescent conditions (11) is another specific structural indication of molecular-level polymorphism in A $\beta$ <sub>1-40</sub> fibrils.

In this paper, we describe new solid state NMR measurements on A $\beta$ <sub>1-40</sub> fibrils that provide direct constraints on quaternary structure. Most of the data presented below were obtained on fibrils grown with gentle agitation (or from seeds that were grown with gentle agitation, as previously described (11)). Mass-per-length (MPL) measurements by scanning transmission electron microscopy have shown that the basic structural unit in these fibrils contains two layers of A $\beta$ <sub>1-40</sub> molecules in a cross- $\beta$  motif (7,11). Data described above indicate that each layer of molecules consists of two  $\beta$ -sheet layers. Thus, the protofilament (*i.e.*, the experimentally observed structural unit with minimum MPL) in agitated A $\beta$ <sub>1-40</sub> fibrils is a four-layered  $\beta$ -sheet structure with both "internal" and "external" quaternary contacts, as depicted in Fig. 1. Internal contacts are those between  $\beta$ -sheets within a single molecular layer, while external contacts are those between  $\beta$ -sheets in different molecular layers. The data presented below indicate internal quaternary contacts between sidechains of L17 and F19 and sidechains of I32, L34, and V36, external quaternary contacts between the sidechain of I31 and the peptide backbone at G37, and external quaternary contacts between the sidechain of M35 and the peptide backbone at G33. These data support the C<sub>2z</sub> quaternary structure in Fig. 1a, with the F19/L34 peptide conformation in Fig. 1b.

In addition, we present limited data for A $\beta$ <sub>1-40</sub> fibrils grown under quiescent conditions. These data provide additional evidence that the internal quaternary contacts in agitated and quiescent fibrils are different. Finally, we report the results of isotopic dilution experiments, in which fibrils were grown from mixtures of <sup>15</sup>N,<sup>13</sup>C-labeled and unlabeled peptides. The effects of isotopic dilution permit distinctions between intramolecular and intermolecular contacts to be made, with implications for the alignment of internal quaternary contacts and the resemblance of amyloid fibril structures to those of  $\beta$ -helical proteins.

## Materials and Methods

### Sample preparation

A $\beta$ <sub>1-40</sub> peptides were synthesized, purified, and fibrillized exactly as previously described (11). The amino acid sequence is DAEFRHDSGY EVHHQKLVFF AEDVGSNKGA IIGLMVGGVV. Fibrils were grown at 22 ± 2° C, with 210  $\mu$ M peptide concentration, 10 mM sodium phosphate buffer, pH 7.4, and 0.01% NaN<sub>3</sub>. Initial dissolution of A $\beta$ <sub>1-40</sub> in buffer and pH adjustment were performed as described, leading to fibril structures that were reproducible and independent of sample-to-sample variations in the initial state of the purified peptide. Parent fibrils were grown either with gentle rotary agitation in horizontal polypropylene tubes or in quiescent dialysis tubes suspended in buffer. Growth of daughter fibrils from seeds (*i.e.*, from sonicated fragments of agitated or quiescent parent fibrils) was carried out in dialysis tubes. As shown by Petkova *et al.*, seeded growth leads to self-propagation of both fibril morphology as seen by EM and fibril structure as seen by solid state NMR (11). The structural homogeneity of all fibril samples was verified by both EM and solid state <sup>13</sup>C NMR.

Samples were synthesized with uniformly <sup>15</sup>N,<sup>13</sup>C-labeled residues at selected positions that were chosen to maximize spectral resolution in two-dimensional (2D) <sup>13</sup>C NMR spectra and to permit searches for particular quaternary contacts. Labeled positions for samples used in the experiments described below are listed in Table 1.

Except as noted below, solid state NMR measurements were carried out on lyophilized fibrils, prepared by centrifugation of the fibril growth solutions, removal of the supernatant, and resuspension of fibrils in deionized water prior to lyophilization. Lyophilized and fully hydrated fibrils exhibit identical  $^{13}\text{C}$  NMR chemical shifts, indicating that lyophilization does not perturb the molecular structure of the fibrils. Lyophilization allowed larger sample quantities to be packed into the magic-angle spinning (MAS) NMR rotors and higher MAS frequencies to be achieved, as required by the measurements.

### Solid state NMR spectroscopy

Experiments were performed at 9.39 T and 14.1 T fields (100.4 MHz, 100.8 MHz, and 150.6 MHz  $^{13}\text{C}$  NMR frequencies) using Varian Infinity and InfinityPlus spectrometers and Varian MAS probes with 3.2 mm diameter MAS rotors. Experiments were performed at room temperature. Rotors typically contained 5-10 mg of lyophilized  $\text{A}\beta_{1-40}$  fibrils compressed into a solid plug, with teflon spacers to contain the fibrils in the center of the NMR detection coil for better radiofrequency (rf) field homogeneity. Proton decoupling fields were typically 110 kHz, with two-pulse phase modulation (63) during chemical shift evolution periods in all pulse sequences.

Quaternary contacts between pairs of  $^{13}\text{C}$ -labeled sites were detected as crosspeaks in 2D  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectra obtained in a 14.1 T field, with MAS frequencies from 16.60 kHz to 23.50 kHz and mixing periods from 500 ms to 1500 ms. In experiments to detect contacts between phenylalanine residues and residues containing methyl groups, the MAS frequency was deliberately set near the difference between NMR frequencies of aromatic and methyl carbons in order to enhance aromatic-to-methyl spin polarization transfers by the rotational resonance effect (64). In some measurements, a proton rf field equal to the MAS frequency was applied during the mixing period (65,66). Presence or absence of this proton rf field did not affect crosspeak intensities significantly with the very long mixing periods employed in these measurements. 2D spectra were obtained in 48-96 hr with a 2 s recycle delay.

Salt bridge interactions between D23 and K28 sidechains were detected through measurements of  $^{15}\text{N}$ - $^{13}\text{C}$  nuclear magnetic dipole-dipole couplings with the frequency-selective rotational echo double resonance (REDOR) technique (67,68). These measurements were carried out at 9.39 T and 14.1 T fields with a 9.00 kHz MAS frequency, 10-15  $\mu\text{s}$  hard  $^{15}\text{N}$   $\pi$  pulse lengths, and frequency-selective Gaussian  $\pi$  pulse lengths (at the NMR frequencies of sidechain amine  $^{15}\text{N}$  and carboxylate  $^{13}\text{C}$  sites) of approximately 1 ms. Each REDOR build-up curve in Fig. 4a was obtained in approximately 170 hr with a 2 s recycle delay.

Quaternary contacts between sidechain methyl  $^{13}\text{C}$  and backbone amide  $^{15}\text{N}$  sites were detected with the 2D transferred echo double resonance (TEDOR) technique of Jaroniec *et al.* (69-71). These measurements were carried out at 14.1 T with an 11.14 kHz MAS frequency and 50 kHz rf fields for all  $^{13}\text{C}$  and  $^{15}\text{N}$  pulses. No frequency-selective pulses were used. 2D  $^{15}\text{N}$ - $^{13}\text{C}$  spectra were obtained in 100-174 hr with a 2 s recycle delay.

$^{13}\text{C}$  NMR chemical shift assignments were obtained previously from 2D  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectra. A table of  $^{13}\text{C}$  NMR chemical shift assignments is available as on-line supporting information for ref. (11).  $^{15}\text{N}$  NMR chemical shift assignments were obtained from 2D  $^{15}\text{N}$ - $^{13}\text{C}$  NMR as in Fig. 6a.  $^{13}\text{C}$  NMR chemical shifts are relative to tetramethylsilane, based on an external adamantane reference at 38.56 ppm.  $^{15}\text{N}$  NMR chemical shifts are relative to liquid  $\text{NH}_3$ , based on the published ratios of  $^{13}\text{C}$  and  $^{15}\text{N}$  NMR frequencies (72).

## Generation of structural models

Structural models depicted in Figs. 1, 7, and 8 were generated with the MOLMOL (73) and TINKER/Force Field Explorer (available at <http://dasher.wustl.edu/tinker/>) programs. The charmm27 force field was used in molecular dynamics (MD) and energy minimization runs in TINKER, with all electrostatic terms switched off. Restraints on certain interatomic distances and backbone torsion angles were enforced by harmonic potential energy functions, as described below.

For each model in Fig. 1b, an initial A $\beta$ 9-40 conformation was constructed in MOLMOL with backbone torsion angles  $\phi = -140^\circ$  and  $\psi = 138^\circ$  for residues 9-24 and 31-40, and with backbone torsion angles chosen manually for residues 25-30 in order to produce approximately the desired internal quaternary contacts while allowing for a salt bridge interaction between D23 and K28 sidechains. Three copies of the initial A $\beta$ 9-40 conformation were combined, with 4.8 Å displacements along the direction of intermolecular hydrogen bonds for the  $\beta$ -strand segments. Restrained energy minimization of the trimeric structure was then carried out. Backbone torsion angles of residues 16-23 and 30-39 were restrained to  $\phi = -140^\circ$  and  $\psi = 140^\circ$ . Intermolecular hydrogen bonds for residues 10-24 and 30-39 in in-register, parallel  $\beta$ -sheets were enforced by 2.15 Å distance restraints between backbone carbonyl oxygen and amide hydrogen atoms. Intramolecular distances between D23 C $_{\gamma}$  and K28 N $_{\zeta}$  were restrained to the 3.5-4.5 Å range. Intramolecular distances between C $_{\alpha}$  of E22 and C $_{\alpha}$  of G33 and between C $_{\alpha}$  of V18 and C $_{\alpha}$  of G37 were restrained to the 8.0-10.0 Å range. Force constants were 0.01 kcal/mol-deg<sup>2</sup> for backbone torsion angles and 10.0 kcal/mol-Å<sup>2</sup> for interatomic distances. Restraints for the four models in Fig. 1b differed only in the choice of backbone hydrogen bond directions for the N-terminal and C-terminal  $\beta$ -strands. Models displayed in Fig. 1b are the central molecules in energy-minimized trimeric structures. Models in Fig. 1a were constructed manually in MOLMOL from multiple copies of the F19/L34 model in Fig. 1b.

For models in Fig. 7, six copies of the F19/L34 model in Fig. 1b were first combined with 4.8 Å displacements along the direction of intermolecular hydrogen bonds. Restrained energy minimization of the hexameric structure was then carried out, followed by a 10-100 ps restrained MD simulation at 400 K and a final restrained energy minimization. Restraints included the backbone torsion angle and intermolecular hydrogen bond distance restraints described above, in addition to 4.0-6.0 Å distance restraints between F19 C $_{\zeta}$  and I32 C $_{\delta}$ , between F19 C $_{\zeta}$  and L34 C $_{\delta}$ , and between F19 C $_{\zeta}$  and V36 C $_{\gamma}$ , and 3.5-4.5 Å distance restraints between D23 C $_{\gamma}$  and K28 N $_{\zeta}$ . These sidechain distance restraints were intermolecular, connecting D23 and F19 of molecule *i* with K28, I32, L34, and V36 of molecule *i*+1, *i*-1, *i*+2, or *i*-2 in order to produce the STAG(+1), STAG(-1), STAG(+2), and STAG(-2) models.

For models in Fig. 8, twelve copies of the F19/L34 model in Fig. 1b were first positioned manually in MOLMOL to approximate a C<sub>2z</sub> structure with the internal and external quaternary contacts indicated by solid state NMR data in Figs. 2-6. Several rounds of restrained energy minimization and restrained MD at 500 K were then performed until STAG(+2) or STAG(-2) stagger was achieved, using a temporary restraint set that included backbone torsion angle restraints for residues 10-12, 15-21, 30-32, 34-36, and 39 ( $\phi = -150^\circ$ ,  $\psi = 150^\circ$ , 0.01 kcal/mol-deg<sup>2</sup> force constants), backbone hydrogen bond distance restraints for residues 10-24 and 30-40 (2.15 Å oxygen-hydrogen distances, 10.0 kcal/mol-Å<sup>2</sup> force constants), intermolecular distance restraints between F19 C $_{\zeta}$  and I32 C $_{\delta}$ , F19 C $_{\zeta}$  and L34 C $_{\delta}$ , and F19 C $_{\zeta}$  and V36 C $_{\gamma}$  (2.0-8.0 Å ranges, 1.0 kcal/mol-Å<sup>2</sup> force constants), between M35 C $_{\epsilon}$  and G33 N (2.0-4.0 Å range, 0.1 kcal/mol-Å<sup>2</sup> force constant), between I31 C $_{\delta}$  and G37 C $_{\alpha}$  (2.0-8.0 Å range, 0.1 kcal/mol-Å<sup>2</sup> force constant), between D23 C $_{\gamma}$  and K28 N $_{\zeta}$  (3.0-4.5 Å distance, 10.0 kcal/mol-Å<sup>2</sup> force constant), and between V12 C $_{\alpha}$  and V40 C $_{\gamma}$ , L17 C $_{\gamma}$  and M35 C $_{\omega}$ , and Q15 C $_{\delta}$  and G37 C $_{\alpha}$  (3.0 Å, 10.0 kcal/mol-Å<sup>2</sup> force constants), and intramolecular distance restraints between M35 C $_{\epsilon}$  and G37 C $_{\alpha}$  (2.0-6.0 Å, 0.1 kcal/mol-Å<sup>2</sup> force constant). In this temporary restraint



set, F19/I32, F19/L34, F19/V36, D23/K28, V12/V40, L17/M35, and Q15/G37 distance restraints were between peptide molecule *i* and molecule *i* + 2 or *i* - 2 within a single molecular layer (representing internal quaternary contacts), to produce the models in Fig. 8a or Fig. 8b. M35/G33 and I31/G37 distance restraints were between molecules in different molecular layers (representing external quaternary contacts).

Once the desired stagger of internal quaternary contacts was achieved, the restraint set was changed to its final form by eliminating the V12/V40, L17/M35, and Q15/G37 distance restraints, reducing the force constants for F19/I32, F19/L34, and F19/V36 distance restraints to 0.1 kcal/mol-Å<sup>2</sup>, and adding intermolecular distance restraints between L17 C<sub>δ</sub> and I32 C<sub>δ</sub> (2.0-8.0 Å range, 0.1 kcal/mol-Å<sup>2</sup> force constant). In the final restraint set, F19/I32, F19/L34, F19/V36, D23/K28, and L17/I32 sidechain distance restraints were between molecule *i* and molecules *i*+1 and *i*+2 or between molecule *i* and molecules *i*-1 and *i*-2 within a single molecular layer. Ten rounds of alternating restrained energy minimizations and restrained MD simulations at 500 K for 5 ps were performed with the final restraints (all of which are based on experimental data) to generate a bundle of structural models. The high-temperature MD simulations produced significant conformational rearrangements between energy minimizations, so that the final bundle of structural models depicts the extent to which the Aβ<sub>1-40</sub> fibril structure is determined by the experimentally-based restraints.

We emphasize that many structural details in the models in Fig. 8 (*e.g.*, backbone and sidechain torsion angles) are not determined uniquely or precisely by the experimental data. This point is discussed in greater detail below.

## Results

### Constraints on internal quaternary contacts

Fig. 2 shows a 2D <sup>13</sup>C-<sup>13</sup>C NMR spectrum of Aβ<sub>1-40</sub>-L1 fibrils, obtained with a 500 ms mixing period between the two spectroscopic dimensions. Under the conditions of this measurement, crosspeaks are detected that connect <sup>13</sup>C NMR chemical shifts of <sup>13</sup>C-labeled sites in nonsequential residues. In contrast, only intra-residue crosspeaks are detected in analogous spectra with mixing periods less than 50 ms (data not shown). Of particular interest are crosspeaks between the aromatic <sup>13</sup>C NMR lines of F19 and aliphatic <sup>13</sup>C NMR lines of I32 and V36, which indicate interatomic distances of approximately 6 Å or less (see below) between the F19 sidechain and the I32 and V36 sidechains. Given the secondary structure of Aβ<sub>1-40</sub> fibrils depicted in Fig. 1, we interpret the observed F19/I32 and F19/V36 crosspeaks as support for internal quaternary contacts resembling those in the F19/L34 model in Fig. 1b.

Fig. 3 shows 1D slices through 2D <sup>13</sup>C-<sup>13</sup>C NMR spectra of several samples with different sets of labeled residues (see Table 1 for sample definitions), all obtained with 500 ms mixing periods. Slices are taken at <sup>13</sup>C NMR chemical shifts of the maximum aromatic signal intensity and of the C<sub>α</sub> NMR lines of I31, I32, L34, or V36. The C<sub>α</sub> slices allow the chemical shifts of the relevant aliphatic sidechain sites to be identified (vertical lines in Fig. 3), due to nearly complete redistribution of <sup>13</sup>C nuclear spin polarizations within each sidechain during the mixing period. The aromatic slices show inter-residue crosspeaks to certain aliphatic sidechain sites, in addition to stronger intra-residue crosspeak to C<sub>α</sub> and C<sub>β</sub> sites of F19 or F20. In Aβ<sub>1-40</sub>-L1 fibrils (Fig. 3a), crosspeaks from F19 to C<sub>γ</sub>1, C<sub>γ</sub>2, and C<sub>δ</sub> sites of I32 (25.4, 16.1, and 12.6 ppm) and to C<sub>β</sub> and C<sub>γ</sub> sites of V36 (33.1 and 19.0 ppm) are observed unambiguously. In Aβ<sub>1-40</sub>-L2 fibrils (Fig. 3c), crosspeaks from F19 to C<sub>γ</sub> and C<sub>δ</sub> of L34 (broad peak at 25 ppm) are observed. In Aβ<sub>1-40</sub>-L3 fibrils (Fig. 3d), crosspeaks from F20 to I32 and V36 are not observed, showing that the aromatic/aliphatic crosspeaks are structurally specific under these measurement conditions. These data support the F19/L34 model in Fig. 1b.

Figs. 3e and 3f provide further evidence for the structural specificity of the 2D  $^{13}\text{C}$ - $^{13}\text{C}$  NMR measurements and for the existence of molecular-level structural polymorphism in  $\text{A}\beta_{1-40}$  fibrils (11).  $\text{A}\beta_{1-40}$ -L4 fibrils grown from quiescent fibril seeds show strong F20/I31 crosspeaks (Fig. 3f). F20/I31 crosspeaks are much weaker or absent in the spectrum of  $\text{A}\beta_{1-40}$ -L4 fibrils grown from agitated fibril seeds (Fig. 3e). Strong F20/I31 crosspeaks in agitated fibrils would be inconsistent with the F19/L34 model in Fig. 1b. Agitated and quiescent  $\text{A}\beta_{1-40}$  fibrils apparently differ in their internal quaternary contacts, in addition to other structural characteristics such as protofilament MPL (11).

In addition to the aromatic/aliphatic contacts identified in Fig. 3, an L17/I32 aliphatic/aliphatic contact was observed in an analogous spectrum of agitated  $\text{A}\beta_{1-40}$  fibrils with uniformly  $^{15}\text{N}$ ,  $^{13}\text{C}$ -labeled S8, H13, L17, V18, A21, I32, and G33 (data not shown).

Interpretation of inter-residue crosspeak intensities in spectra such as those in Figs. 2 and 3 in terms of precise distances between specific pairs of  $^{13}\text{C}$ -labeled sites is not possible because these crosspeak intensities are determined by a network of magnetic dipole-dipole couplings, both intra-residue and inter-residue, among many  $^{13}\text{C}$  nuclei with unknown geometry. Couplings to  $^1\text{H}$  nuclei also play a large role, making accurate numerical simulations for any given geometry intractable. In order to obtain an empirical estimate of the distance range probed by our 2D  $^{13}\text{C}$ - $^{13}\text{C}$  NMR measurements, we have measured the extent of nuclear spin polarization transfer from aromatic  $^{13}\text{C}$  sites to aliphatic  $^{13}\text{C}$  sites in a sample of polycrystalline Phe-Val, a dipeptide with known crystal structure (74). In this sample, molecules with uniformly  $^{15}\text{N}$ ,  $^{13}\text{C}$ -labeled phenylalanine were cocrystallized with molecules with uniformly  $^{15}\text{N}$ ,  $^{13}\text{C}$ -labeled valine, in a 1:5 molar ratio. Experimental conditions were essentially the same as in Figs. 2 and 3. After mixing periods of 100 ms, 200 ms, and 500 ms, nuclear spin polarizations of valine aliphatic sites were  $4.4 \pm 0.4\%$ ,  $8.8 \pm 0.4\%$ , and  $19 \pm 2\%$  of the nuclear spin polarizations of phenylalanine aromatic sites, as determined from  $^{13}\text{C}$  NMR signal intensities. Fitting these data to an exponential form, we extract a characteristic time  $\tau = 2300$  ms for intermolecular aromatic-to-aliphatic polarization transfer in Phe-Val. The shortest intermolecular distances between aromatic and aliphatic carbons in Phe-Val are 3.9 Å (74). If  $\tau \propto R^6$ , as might be expected for incoherent polarization transfer between isolated pairs of dipole-coupled  $^{13}\text{C}$  nuclei with internuclear distance  $R$ , if  $R = 3.9$  Å for Phe-Val, and if a 10% polarization transfer were detectable, then the maximum detectable distance would be  $R_{\text{max}} \approx 4.4$  Å. If  $\tau \propto R^2$ , as might be expected if polarization transfer were a diffusive process, then  $R_{\text{max}} \approx 5.6$  Å. Based on these results, we estimate that the inter-residue crosspeaks discussed above indicate interatomic distances up to approximately 6 Å. Note that this distance estimate applies to the shortest distance between  $^{13}\text{C}$ -labeled sites of the two residues in question. Distance limits of 8 Å are used in the modeling calculations (see Materials and Methods) due to the unknown identities of the closest sites. These distance limits are consistent with the interpretation of inter-residue  $^{13}\text{C}$ - $^{13}\text{C}$  crosspeaks in similar measurements on microcrystalline proteins of known structure (75).

Shortest intramolecular distances between sidechain carbon nuclei of F19 and sidechain carbon nuclei of I32, L34, and V36 are 3.8 Å, 3.9 Å, and 7.8 Å for the F19/L34 model in Fig. 1b, 15.3 Å, 10.1 Å, and 8.0 Å for the F20/L34 model, 7.0 Å, 7.8 Å, and 12.4 Å for the F19/M35 model, and 18.3 Å, 15.5 Å, and 15.2 Å for the F20/M35 model. These are distances in models generated without inclusion of F19/I32, F19/L34, or F19/V36 distance restraints, but they strongly suggest that only the F19/L34 model has quaternary contacts consistent with data in Figs. 2 and 3.

### D23/K28 salt bridge interaction

Fig. 4a shows  $^{13}\text{C}$ -detected frequency-selective REDOR data for  $\text{A}\beta_{1-40}$ -L4. In these measurements, frequency-selective rf pulses permit detection of the  $^{15}\text{N}$ - $^{13}\text{C}$  magnetic dipole-

dipole coupling between  $C_\gamma$  of D23 and  $N_\zeta$  of K28, despite the presence of multiple  $^{15}\text{N}$ - and  $^{13}\text{C}$ -labeled sites in  $\text{A}\beta_{1-40}$ -L4 (68). For isolated  $^{15}\text{N}$ - $^{13}\text{C}$  pairs with internuclear distance  $R_{\text{NC}}$ , one expects a build-up of the REDOR  $\Delta S/S_0$  signal with increasing evolution period  $\tau_{\text{REDOR}}$  such that  $\Delta S/S_0$  reaches half its maximum value at  $\tau_{\text{REDOR}} = 0.257 \text{ ms} \times \delta (R_{\text{NC}}^3/\text{\AA}^3)$  (41,67,68). If each  $^{13}\text{C}$  nucleus is coupled to more than one  $^{15}\text{N}$  nucleus, the REDOR build-up curve is dominated by the shortest  $^{15}\text{N}$ - $^{13}\text{C}$  distance. Therefore, the data for  $\text{A}\beta_{1-40}$ -L4 in Fig. 4a, in which the half-maximum occurs at  $12.5 \pm 1.5 \text{ ms}$ , indicate nearest-neighbor  $^{15}\text{N}$ - $^{13}\text{C}$  distances of approximately  $3.7 \text{ \AA}$ , consistent with salt bridge interactions between the sidechains of D23 and K28.

The spectra in Fig. 4b demonstrate the selectivity of our frequency-selective REDOR data. The intensities of D23  $^{13}\text{C}_\gamma$  NMR lines (at 180.8 ppm) differ significantly in  $S_0$  and  $S_1$  spectra. The intensities of the backbone  $^{13}\text{CO}$  signals (at 173 ppm) are the same in  $S_0$  and  $S_1$  spectra, despite the fact that every backbone  $^{13}\text{CO}$  label is within approximately  $2.4 \text{ \AA}$  of a backbone amide  $^{15}\text{N}$  label.

As shown previously (10), NMR chemical shifts indicate that the D23 and K28 sidechains are ionized in  $\text{A}\beta_{1-40}$  fibrils. Frequency-selective REDOR measurements have shown the absence of D23/K28 salt bridge interactions in fibrils grown under quiescent conditions (11).

### Constraints on external quaternary contacts

Fig. 5 shows 2D  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectra of  $\text{A}\beta_{1-40}$ -L5 fibrils. With a 1500 ms mixing period, but not a 200 ms period, crosspeaks between the  $^{13}\text{C}_\alpha$  NMR line of G37 and aliphatic  $^{13}\text{C}$  NMR lines of I31 are observed unambiguously (blue arrows in G37 $\alpha$  slice, Fig. 5b). Given that I31 and G37 reside in a single  $\beta$ -strand, the intramolecular distances between G37  $C_\alpha$  and I31 aliphatic sites are approximately  $20 \text{ \AA}$ , too large to produce the observed crosspeaks. We therefore attribute the G37/I31 crosspeaks to external quaternary contacts, favoring the  $C_{2z}$  model over the  $C_{2x}$  model in Fig. 1a. Strong I31/M35 crosspeaks are also observed (blue arrows in M35 $\epsilon$  slice, Fig. 5b), consistent with the  $C_{2z}$  model. The fact that crosspeaks between the  $^{13}\text{C}_\alpha$  NMR line of G37 and the  $^{13}\text{C}_\epsilon$  NMR line of M35 are more intense than the corresponding G33/M35 crosspeaks (red arrow in G37 $\alpha$  slice and purple arrows in M35 $\epsilon$  slice, Fig. 5b) suggests that the M35 sidechain tilts toward G37 rather than G33, as depicted in the F19/L34 model in Fig. 1b.

Additional constraints on external quaternary contacts in  $\text{A}\beta_{1-40}$  fibrils come from the 2D  $^{15}\text{N}$ - $^{13}\text{C}$  NMR spectrum in Fig. 6. The spectrum in Fig. 6a, obtained with 2.87 ms  $^{15}\text{N}$ - $^{13}\text{C}$  TEDOR evolution periods, shows strong intra-residue  $^{13}\text{C}_\alpha/^{15}\text{N}$  crosspeaks that permit site-specific assignment of backbone amide  $^{15}\text{N}$  chemical shifts for labeled residues in  $\text{A}\beta_{1-40}$ -L5 fibrils. With 5.75 ms TEDOR periods (Fig. 6b), crosspeaks between sidechain methyl  $^{13}\text{C}$  NMR lines and backbone amide  $^{15}\text{N}$  NMR lines become more intense, while  $^{13}\text{C}_\alpha/^{15}\text{N}$  crosspeaks are attenuated by the relatively rapid transverse spin relaxation of  $^{13}\text{C}_\alpha$ . A strong crosspeak between the  $^{13}\text{C}_\epsilon$  NMR line of M35 and the  $^{15}\text{N}$  line of G33 is observed, while the corresponding M35/G37 crosspeak is absent. We attribute the M35/G33 crosspeak to an external contact between the M35 sidechain and the peptide backbone at G33. The fact that the volume of the crosspeak between  $^{13}\text{C}_\epsilon$  of M35 and  $^{15}\text{N}$  of G33 is about equal to the volumes of intra-residue  $^{13}\text{CO}/^{15}\text{N}$  crosspeaks suggests that the intermolecular distance between  $C_\epsilon$  of M35 and N of G33 is roughly  $3 \text{ \AA}$ .

Fig. 6c shows that the M35/G33 crosspeak intensity is reduced by a factor of two or more (relative to the intra-residue  $^{13}\text{CO}/^{15}\text{N}$  crosspeak of G33) when  $\text{A}\beta_{1-40}$ -L5 is diluted to 33% in unlabeled  $\text{A}\beta_{1-40}$ , producing the  $\text{A}\beta_{1-40}$ -L5d fibril sample. This result indicates that the approximate  $3 \text{ \AA}$  distance between  $C_\epsilon$  M35 and N of G33 is an intermolecular distance,



consistent with our interpretation of the M35/G33 crosspeak as evidence for an external quaternary contact.

$C_{2z}$  symmetry is also favored over  $C_{2x}$  symmetry by the observation of a single set of  $^{13}\text{C}$  NMR chemical shifts for sidechain sites in  $\text{A}\beta_{1-40}$ -L5 fibrils. Interdigitation of sidechains at the external interface would necessarily lower the symmetry of a  $C_{2x}$  structure (76), shifting the two molecular layers relative to one another and placing the I31, M35, and V39 sidechains of the two layers in qualitatively different structural environments. One would then expect to observe splittings of the  $^{13}\text{C}$  NMR lines due to structural inequivalence of the two molecular layers at the external quaternary contacts. No splittings are observed in Fig. 4 or in any other spectra of  $\text{A}\beta_{1-40}$ -L5 fibrils.

In all-atom representations of the models in Fig. 1a, the shortest distance between sidechain nuclei of I31 and  $\text{C}_\alpha$  of G37 is 5.2 Å for  $C_{2z}$  symmetry and 19.1 Å for  $C_{2x}$  symmetry. Both symmetries lead to 4.6 Å distances between  $\text{C}_\epsilon$  of M35 and N of G33 in different molecular layers, but only half of the  $\text{C}_\epsilon$  nuclei participate in a 4.6 Å distance with  $C_{2x}$  symmetry. The shortest distance is 16.4 Å for the remaining  $\text{C}_\epsilon$  nuclei. These are distances in models generated without inclusion of distance restraints based on the data in Figs. 2, 3, 5, and 6, but they strongly suggest that  $C_{2z}$  symmetry is consistent with the experimental data, while  $C_{2x}$  symmetry is not.

### Staggering of internal quaternary contacts

When a single peptide molecule contributes  $\beta$ -strand segments to more than one  $\beta$ -sheet in an amyloid fibril, the displacement of the  $\beta$ -sheets along the direction of the long fibril axis becomes an additional structural variable that we refer to as "stagger". Fig. 7 shows idealized models for a single molecular layer in  $\text{A}\beta_{1-40}$  fibrils with four distinct staggers. In the STAG(+1) and STAG(-1) models, the C-terminal  $\beta$ -strand of each molecule is displaced by approximately 2.4 Å (*i.e.*, half the interstrand spacing in one  $\beta$ -sheet) relative to the N-terminal  $\beta$ -strand of the same molecule. Note that the two ends of a fibril constructed from in-register, parallel  $\beta$ -sheets are inequivalent, with backbone amide N-H bonds of even-numbered residues and odd-numbered residues in the same  $\beta$ -sheet pointing towards opposite ends. Therefore, STAG(+1) and STAG(-1) models are structurally distinct. In the STAG(+2) and STAG(-2) models, the C-terminal  $\beta$ -strand of each molecule is displaced by approximately 7.2 Å (*i.e.*, 1.5 times the interstrand spacing) relative to the N-terminal  $\beta$ -strand of the same molecule. Displacements by odd multiples of half the interstrand spacing are expected to optimized the packing of sidechains at interfaces between  $\beta$ -sheets. The size of the displacement is obviously limited by the length of the loops between  $\beta$ -strand segments.

STAG( $\pm 1$ ) and STAG( $\pm 2$ ) models differ as to whether internal quaternary contacts (*e.g.*, the F19/I32 and F19/V36 contacts indicated by the data in Figs. 2 and 3a) are both intramolecular and intermolecular (for STAG( $\pm 1$ ) models) or purely intermolecular (for STAG( $\pm 2$ ) models). In principle, comparisons of solid state NMR data from fibrils in which all peptide molecules are isotopically labeled with data from fibrils in which only a fraction of the molecules are labeled permits intramolecular contacts to be distinguished intermolecular contacts. Figs. 3 and 4 show the results of such isotopic dilution experiments. Dilution of  $\text{A}\beta_{1-40}$ -L1 in unlabeled  $\text{A}\beta_{1-40}$ , producing the  $\text{A}\beta_{1-40}$ -L1d sample, results in a reduction of F19/I32 crosspeak intensities relative to intra-residue F19 crosspeak intensities by a factor of  $0.50 \pm 0.15$  (Figs. 3a and 3b). F19/V36 crosspeak intensities are reduced by a factor of  $0.40 \pm 0.20$ . Assuming that F19/I32 or F19/V36 crosspeak intensities (normalized to intraresidue crosspeak intensities) are proportional to the average number of quaternary contacts of a labeled F19 sidechain to labeled sidechains of I32 or V36, one expects a reduction of intra-residue crosspeak intensity by a factor of 0.65 for 31% labeling in STAG( $\pm 1$ ) structures (factor of  $(1+x)/2$  for labeled fraction  $x$ ) and a factor of 0.31 for 31% labeling in STAG( $\pm 2$ ) structures (factor of  $x$ ).

In Fig. 4a, dilution of  $A\beta_{1-40}$ -L4 in unlabeled  $A\beta_{1-40}$ , producing the  $A\beta_{1-40}$ -L4d sample, results in a reduction of the  $\Delta S/S_0$  values in frequency-selective REDOR data by a factor of  $0.50 \pm 0.07$ . Assuming that each D23 sidechain interacts with two K28 sidechains (due to interdigitation of the oppositely charged sidechains (76)) and that the  $\Delta S/S_0$  value is proportional to the probability that a labeled D23 sidechain interacts with at least one labeled K28 sidechain, one expects no reduction of  $\Delta S/S_0$  in STAG( $\pm 1$ ) structures and a reduction by 0.44 for 33% labeling in STAG( $\pm 2$ ) structures (factor of  $(1-x)^2$ ). Thus, the combined data for  $A\beta_{1-40}$ -L1d and  $A\beta_{1-40}$ -L4d fibril samples favor STAG( $\pm 2$ ) models.

## Discussion

### Explicit structural models for $A\beta_{1-40}$ fibrils

Fig. 8 shows explicit models for the molecular structure of  $A\beta_{1-40}$  fibrils, constructed with the high-temperature MD/energy minimization protocol described above (see Materials and Methods). Because our data do not distinguish STAG(+2) from STAG(-2) structures, models with both staggers are shown. Residues 1-8 are omitted, as these residues are known to be structurally disordered from solid state NMR linewidth data (10,11), measurements of intermolecular  $^{13}\text{C}$ - $^{13}\text{C}$  dipole-dipole couplings (37,38), hydrogen exchange data (26,27), and proteolysis data (61,62). All structural restraints used in the final MD/energy minimization protocol were based on experimental measurements, including previously reported NMR chemical shift data (11) and intermolecular distance measurements (37,38) in addition to the data in Figs. 2-6. Atomic coordinates are available upon request (e-mail address: robertty@mail.nih.gov).

The STAG(+2) (Figs. 8a, 8b, and 8e) and STAG(-2) (Figs. 8c and 8d) models are quite similar. In both models, sidechains of L17, F19, I32, L34, and V36 create a hydrophobic cluster that apparently stabilizes the fold of a single molecular layer (*i.e.*, the internal quaternary contacts). Glycines at residues 33, 37, and 38 create grooves into which the sidechains of I31 and M35 fit at the interface between molecular layers (*i.e.*, the external quaternary contacts). Oppositely charged D23 and K28 sidechains interact in an intermolecular fashion, but in the interior of a single molecular layer with STAG( $\pm 2$ ) stagger. Models in Fig. 8 contain channels that are lined by sidechains of F19, A21, D23, K28, A30, and I32. These channels may contain "water wires", as suggested by recent MD simulations in explicit solvent (76). We find that the  $^{13}\text{C}$  NMR linewidths for D23 and K28 sidechain sites are reduced significantly in hydrated  $A\beta_{1-40}$  fibrils compared with those in lyophilized  $A\beta_{1-40}$  fibrils (*e.g.*, 2.0 ppm, 1.5 ppm, and 1.2 ppm for  $C_\gamma$ ,  $C_\delta$ , and  $C_\epsilon$  of K28 in the hydrated state, compared with  $>2.5$  ppm in the lyophilized state), possibly due to motional narrowing associated with mobile water molecules in these channels. Other charged and polar sidechains are outside the hydrophobic core of the models in Fig. 8.

$A\beta_{1-40}$  molecules with oxidized M35 sidechains have been shown to be resistant to fibril formation, relative to unoxidized  $A\beta_{1-40}$  (77,78). Oxidation greatly increases the polarity of the M35 sidechain (79), possibly destabilizing the external quaternary contacts and thereby inhibiting fibril formation.

Models in Fig. 8 represent the  $A\beta_{1-40}$  protofilament, *i.e.*, the minimal structural unit in  $A\beta_{1-40}$  fibrils. In EM images of agitated  $A\beta_{1-40}$  fibrils, the protofilaments have widths of  $50 \pm 5$  Å and typically associate in a parallel manner, forming flat bundles of 2-5 protofilaments (11). The protofilament diameters, as measured by the distances between V12  $C_\alpha$  sites in the two different molecular layers, are  $49 \pm 1$  Å in both Fig. 8a and Fig. 8b. The nature of contacts between protofilaments in agitated  $A\beta_{1-40}$  fibrils is unknown. Intermolecular salt bridges between K16 and E22 sidechains, proposed as possible interactions between protofilaments in our earlier work (10), were not detected in subsequent frequency-selective REDOR measurements on agitated  $A\beta_{1-40}$  fibrils (11). If each individual protofilament has nonzero

twist about its long axis, as depicted in Fig. 8e, then contacts between protofilaments would vary along the length of the fibril and would not be detectable in our solid state NMR data. At present, we do not have experimental constraints on the twist of individual protofilaments.

### Possibility of alternative models

The ratio of structural constraints to amino acid residues in this work is small compared to the analogous ratio in typical structural studies of globular proteins by liquid state NMR techniques. It is therefore reasonable to ask whether alternative models for A $\beta$ <sub>1-40</sub> fibril structure might also be consistent with the available constraints. As pointed out previously (80), the experimental determination of amyloid structures is greatly simplified by the fact that these structures must be of the cross- $\beta$  type. In the case of A $\beta$ <sub>1-40</sub> fibrils, the constraint that the  $\beta$ -strand segments form in-register, parallel  $\beta$ -sheets with cross- $\beta$  orientation means that relatively few structures are possible once the  $\beta$ -strand segments are identified. MPL data and measurements of fibril dimensions from EM or atomic force microscopy further restrict the number of possible structures. Finally, realistic models must make sense in light of known principles governing the stability of proteins and the fact that the fibrils form in aqueous environments. We have been unable to construct models (even schematically) that are qualitatively different from those in Fig. 8 and yet satisfy the same set of experimental constraints.

Given that L17 and F19 reside in the same  $\beta$ -strand and that I32, L34, and V36 reside in the same  $\beta$ -strand, no sets of internal and external quaternary contacts different from those discussed above appear possible. Proximity of I31 and G37, indicated by the data in Fig. 5, requires that contacts between the two molecular layers involve the second  $\beta$ -strand. Proximity of sidechains of L17 and F19 to sidechains of I32, L34, and V36 then requires that these sidechains be in the interior of a molecular layer, making internal quaternary contacts. The D23/K28 salt bridge interactions must also occur in the interior of a molecular layer. If the D23/K28 interactions were between different molecular layers, then the C<sub>2z</sub> symmetry would be lost and only half of the D23 and K28 sidechains could participate in these interactions. This would contradict the experimental observation of  $\Delta S/S_0$  values greater than 0.5 in Fig. 4a. If the D23/K28 interactions were on the exterior of a molecular layer, then we would expect these interactions to be different in hydrated and lyophilized A $\beta$ <sub>1-40</sub> fibrils. In fact, we have measured indistinguishable REDOR  $\Delta S/S_0$  values in hydrated and lyophilized samples.

On the other hand, A $\beta$ <sub>1-40</sub> fibrils grown under different conditions can have different dimensions, morphologies, MPL values, and NMR spectra, and therefore qualitatively different molecular structures, as we have demonstrated previously for the quiescent and agitated morphologies (11) and as reinforced by data in Fig. 3. Although we do not yet have full structural models for quiescent A $\beta$ <sub>1-40</sub> fibrils or for other morphologies, some morphologies may contain the alternative quaternary structures depicted in Fig. 1. The alternative structures also appear stable with respect to hydrophobic and electrostatic interactions. MD simulations in explicit solvent support the stability of both C<sub>2z</sub> and C<sub>2x</sub> structures, with both F19/L34 and F19/M35 internal quaternary contacts, on time scales exceeding 10 ns (76). The nonspecific nature of hydrophobic interactions, which are apparently the primary stabilizing interactions in A $\beta$ <sub>1-40</sub> fibrils and in fibrils formed by certain other peptides (8,10,37,41), may account for the polymorphism of A $\beta$ <sub>1-40</sub> fibrils.

Although the models in Fig. 8 are consistent with available data for agitated A $\beta$ <sub>1-40</sub> fibrils, not all aspects of these models are determined uniquely or precisely by the data. For example, available data do not place direct constraints on sidechain torsion angles. Backbone torsion angles for residues 22-29 are unconstrained, except by the requirement for D23/K28 interactions and internal quaternary contacts. Thus, the models in Fig. 8 are subject to refinement and revision as additional data become available.

## Relation to other proposed models for amyloid structures

Several early structural models for fibrils formed by full-length  $\beta$ -amyloid peptides assumed antiparallel  $\beta$ -sheets and are therefore inconsistent with current data (81-85). The models in Fig. 8 are similar to our  $A\beta_{1-40}$  fibril model published in 2002 (10), but differ in the identity of the internal quaternary contacts (F19/L34 in Fig. 1b, rather than F19/M35) and the symmetry of the protofilament ( $C_{2z}$  rather than  $C_{2x}$ ). Experimental constraints on internal quaternary contacts and protofilament symmetry were not available when the 2002 model was constructed. In addition, the models in Fig. 8 include the intermolecular nature of the internal quaternary contacts and the D23/K28 salt bridge interaction, as supported by the isotopic dilution experiments described above. A model for  $A\beta_{10-35}$  fibrils proposed by Ma and Nussinov, also in 2002, has F19/L34 internal quaternary contacts but completely different external contacts (51).

A closely related structural model for  $A\beta_{1-40}$  fibrils has been proposed by Wetzel and coworkers (29,52), based on proline scanning mutagenesis (29), H/D exchange (27), and disulfide crosslinking (52) experiments, and incorporating the in-register, parallel  $\beta$ -sheet structure established by solid state NMR (37,38). In agreement with the models in Fig. 8, the model of Wetzel and coworkers places the sidechains of L17, F19, I32, L34, and V36 in the interior of a single molecular layer, as supported by the observation of intramolecular disulfide crosslinks after oxidation of fibrils formed by L17C/L34C and L17C/V36C double mutants of  $A\beta_{1-40}$  (52). In contrast to the models in Fig. 8, sidechains of D23 and K28 are on the exterior of a single molecular layer and only residues 15-36 are considered to be structurally ordered in the model of Wetzel and coworkers (29,52). The positions of the D23 and K28 sidechains may have been chosen arbitrarily in the model of Wetzel and coworkers. Alternatively, the positions of these sidechains may reflect polymorphism, as the D23/K28 salt bridge has been shown to be absent in quiescent  $A\beta_{1-40}$  fibrils (11) and fibril growth conditions in the experiments of Wetzel and coworkers are not the same as in our solid state NMR experiments. Disagreement about the extent of structurally ordered segments is likely to arise from differences in the sensitivity of different experimental techniques to disorder. For example, in the site-specific H/D exchange experiments of Whittemore *et al.* (27), backbone amide exchange of roughly 75% or more after a 25 hr period at room temperature and pH 7.5 was interpreted as a signature of structural disorder. These data should be viewed in light of H/D exchange measurements on thermostable globular proteins such as protein  $G_{B2}$  (86), where exchange rates for all backbone amide sites exceed  $0.1 \text{ hr}^{-1}$  at  $22^\circ \text{C}$  and pH 7.0, including all sites in the  $\alpha$ -helix and the  $\beta$ -sheet of protein  $G_{B2}$ . Exchange rates are expected to increase by a factor of 3.2 at pH 7.5. Thus, while the H/D exchange data of Whittemore *et al.* on  $A\beta_{1-40}$  fibrils do indicate that most residues in segments 15-23 and 27-35 are in highly stable structures, residues outside these segments may be in  $\beta$ -sheets whose stability is comparable to that of protein  $G_{B2}$ .

Solid state  $^{13}\text{C}$  NMR linewidths suggest that residues 14-16 and 35-40 may be more disordered than residues 10-13 and 17-34, but measurements of intermolecular  $^{13}\text{C}$ - $^{13}\text{C}$  distances indicate that V12 and V39 are nonetheless in parallel  $\beta$ -sheets (11,38). Thus, we believe that residues 10-39 in  $A\beta_{1-40}$  fibrils are more highly ordered than the N-terminal tail, where larger linewidths are observed and intermolecular  $^{13}\text{C}$ - $^{13}\text{C}$  distances are significantly longer (11,37,38). H/D exchange experiments on  $A\beta_{1-40}$  fibrils by Wang *et al.* (26), using exchange periods of 30 min at  $25^\circ \text{C}$  and  $\text{pH} \approx 7.2$ , indicate that the C-terminal segment is more strongly protected from H/D exchange than the N-terminal segment.

Kajava *et al.* have proposed a general model for the structure of amyloid fibrils which they call a "parallel superpleated  $\beta$ -structure" (54). This model may be considered a generalization of the schematic models in Fig. 1a and of our earlier models (7,10) to higher-molecular-weight systems, such as the amyloid-forming domains of yeast prion proteins (54). In a parallel

superpleated  $\beta$ -structure, each polypeptide chain adopts a "β-serpentine" conformation, consisting of alternating  $\beta$ -strands and bends, and the  $\beta$ -strands form a stack of in-register, parallel  $\beta$ -sheets. The four-layered  $\beta$ -sheet structures in Figs. 1a and 8 resemble the parallel superpleated  $\beta$ -structures envisioned by Kajava *et al.*, except that each  $A\beta_{1-40}$  molecule participates in only two  $\beta$ -sheets.

Ritter *et al.* have proposed a structural model for amyloid fibrils formed by residues 218-289 of the HET-s fungal prion protein (HET-s<sub>218-289</sub>) in which each polypeptide chain participates in two parallel  $\beta$ -sheets, but contributes two  $\beta$ -strand segments to each  $\beta$ -sheet (14). Unlike the models discussed above, in which all backbone hydrogen bonds between  $\beta$ -strands are intermolecular, half of the backbone hydrogen bonds in the model of Ritter *et al.* are intramolecular and half are intermolecular. Additional experimental constraints are needed to confirm the model of Ritter *et al.*, but the proposed pattern of backbone hydrogen bonds is supported by the sequence similarity and charge complementarity of pairs of  $\beta$ -strands within HET-s<sub>218-289</sub> (14). Linewidths in 2D solid state  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectra of HET-s<sub>218-289</sub> fibril samples are less than linewidths in similar spectra of  $A\beta_{1-40}$  fibrils by factors of 3-10, indicating nearly crystalline order in the  $\beta$ -sheets of HET-s<sub>218-289</sub> fibrils (14,87). The exceptionally high level of structural order may be a consequence of the fact that the HET-s prion has a clear biological function (14,88). The amino acid sequence of HET-s<sub>218-289</sub> does not contain long hydrophobic segments and is not rich in glutamine and asparagine residues, suggesting that the HET-s<sub>218-289</sub> amyloid structure is stabilized by a specific set of sidechain interactions that does not admit the structural variations observed in  $A\beta_{1-40}$  fibrils.

Nelson *et al.* have reported crystal structures of the peptides GNNQQNY and NNQQNY that strongly resemble amyloid structures (60). In these crystal structures, each peptide molecule adopts a  $\beta$ -strand conformation and participates in an in-register, parallel  $\beta$ -sheet. Pairs of  $\beta$ -sheets interact through interdigitated sidechain-sidechain and sidechain-backbone contacts. Each pair of  $\beta$ -sheets has  $C_{2z}$  symmetry. Thus, the crystal structures of GNNQQNY and NNQQNY have several important features in common with the  $A\beta_{1-40}$  fibril models in Fig. 8, although the low molecular weight of these peptides prevents a direct comparison of other aspects of symmetry and quaternary interactions.

Finally, several groups have proposed that amyloid fibrils may resemble  $\beta$ -helical proteins (53,85,89,90), which contain rod-like helical structures comprised of alternating  $\beta$ -strand and bend segments, with a cross- $\beta$  orientation of the  $\beta$ -strand segments (91). In a  $\beta$ -helical protein, a single polypeptide chain forms multiple turns of the helix. The idealized STAG(+1) and STAG(-1) models in Fig. 7 may be considered to be right-handed and left-handed helical structures, respectively, with each  $A\beta_{1-40}$  chain forming one turn of the helix, if one links the C-terminus of chain  $i$  with the N-terminus of chain  $i\pm 1$ . Similarly, if one links the C-terminus of chain  $i$  with the N-terminus of chain  $i\pm 2$ , the STAG( $\pm 2$ ) models may be considered to be helical structures comprised of two intertwined chains. One may then consider the models in Fig. 8 to be dimers of  $\beta$ -helices. However, unlike known  $\beta$ -helical proteins, which contain at least three  $\beta$ -strands per turn, each molecular layer in Fig. 8 contains two  $\beta$ -strands per turn. The utility of this analogy between the  $A\beta_{1-40}$  fibril structure and the structures of  $\beta$ -helical proteins remains to be determined.

## Abbreviations

EM, electron microscopy

NMR, nuclear magnetic resonance

H/D, hydrogen/deuterium

EPR, electron paramagnetic resonance

$A\beta_{1-40}$ , 40-residue  $\beta$ -amyloid peptide



MPL, mass-per-length  
 2D, two-dimensional  
 MAS, magic-angle spinning  
 REDOR, rotational echo double resonance  
 TEDOR, transferred echo double resonance  
 MD, molecular dynamics  
 HET-s<sub>218-289</sub>, residues 218-289 of the HET-s protein

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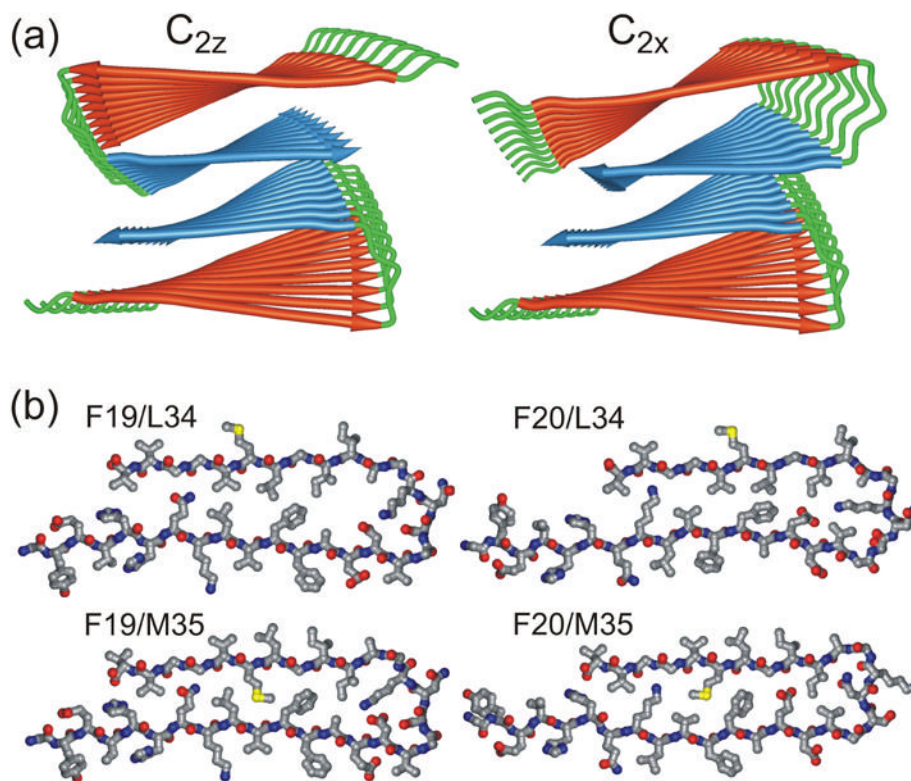
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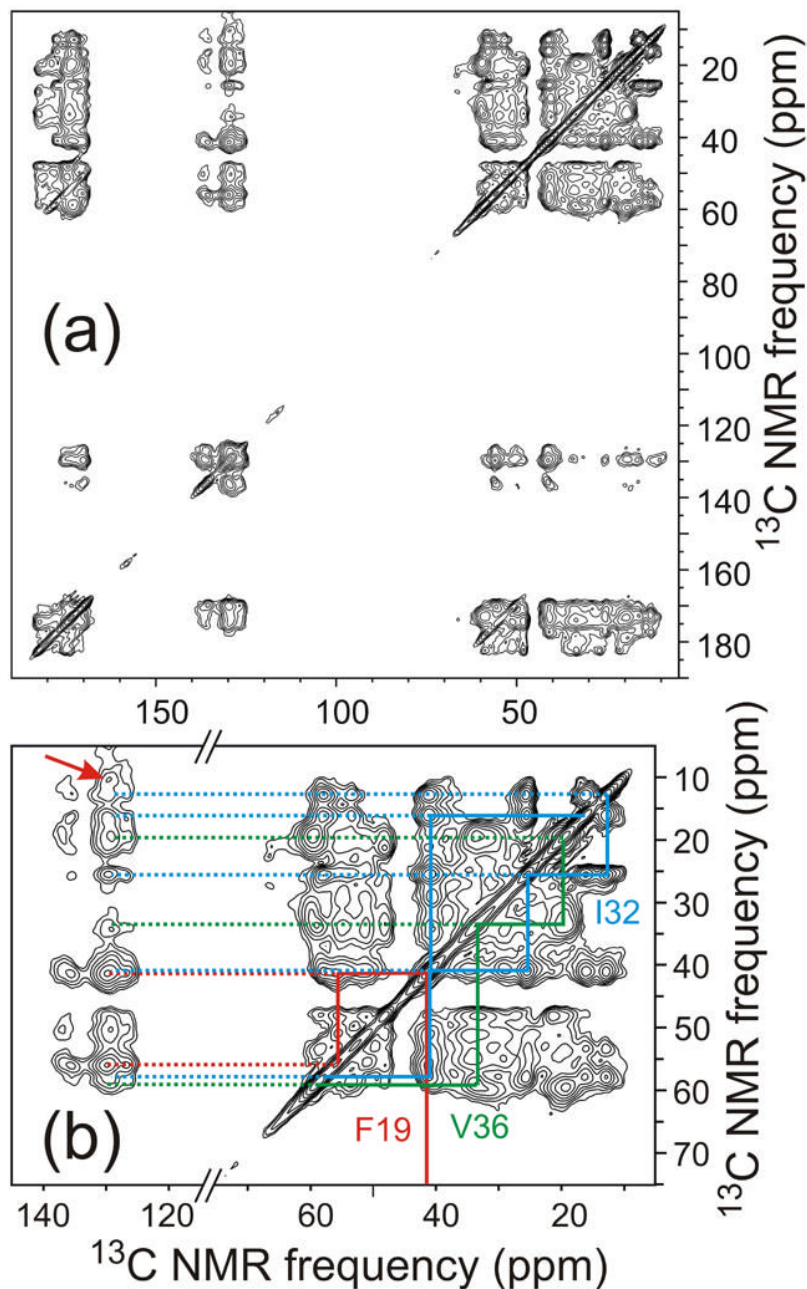
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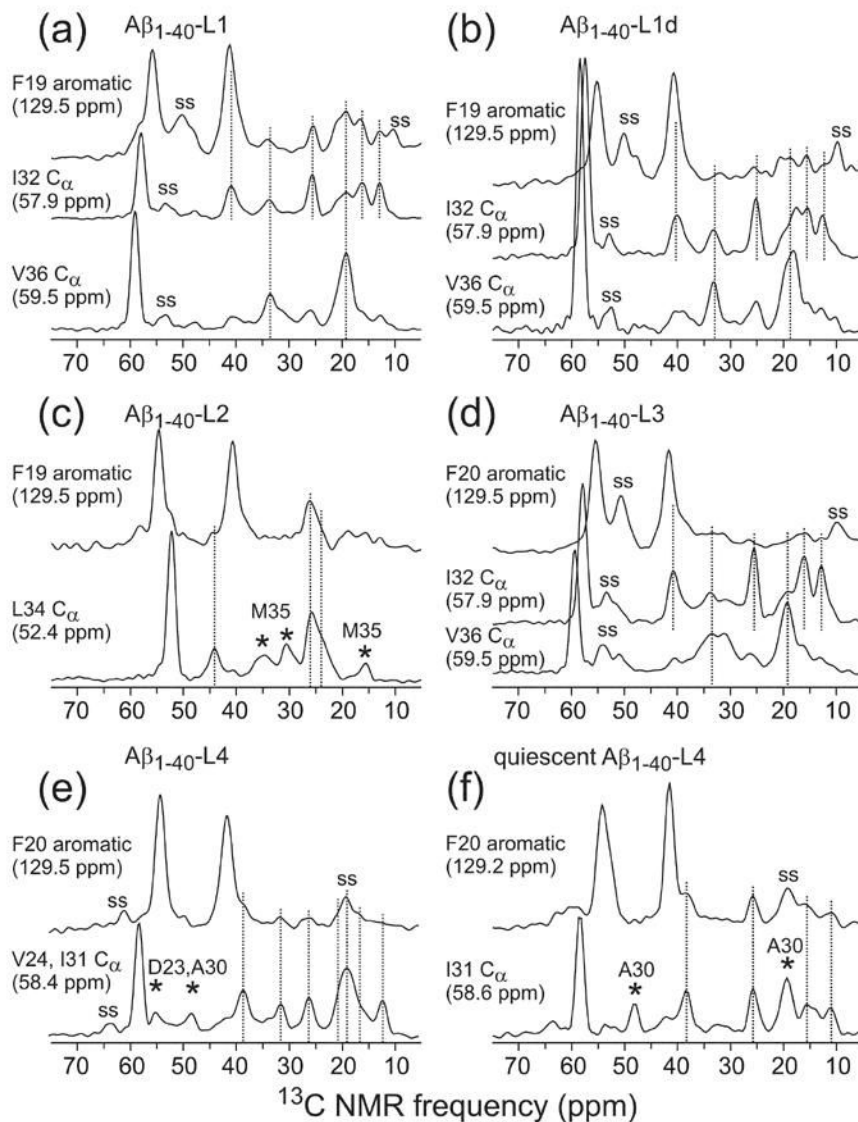
**Figure 1:**

(a) Cartoon representations of candidate quaternary structures for Aβ<sub>1-40</sub> fibrils with either C<sub>2z</sub> or approximate local C<sub>2x</sub> symmetries. The z axis is the long axis of the fibril, approximately perpendicular to the page. The x axis is perpendicular to z and approximately parallel to the β-strands. Each Aβ<sub>1-40</sub> molecule contains two β-strands, colored red (N-terminal β-strand) and blue (C-terminal β-strand), which form separate, parallel β-sheets. Different quaternary structures are distinguished by different sets of sidechain contacts at the "internal" interfaces (between a red and a blue β-sheet) and the "external" interface (between two blue β-sheets). (b) Four possible molecular conformations that lead to different quaternary structures. Quaternary contacts at the internal interface are between F19 and L34, F20 and L34, F19 and M35, or F20 and M35. Residues 1-8 are conformationally disordered and are omitted.

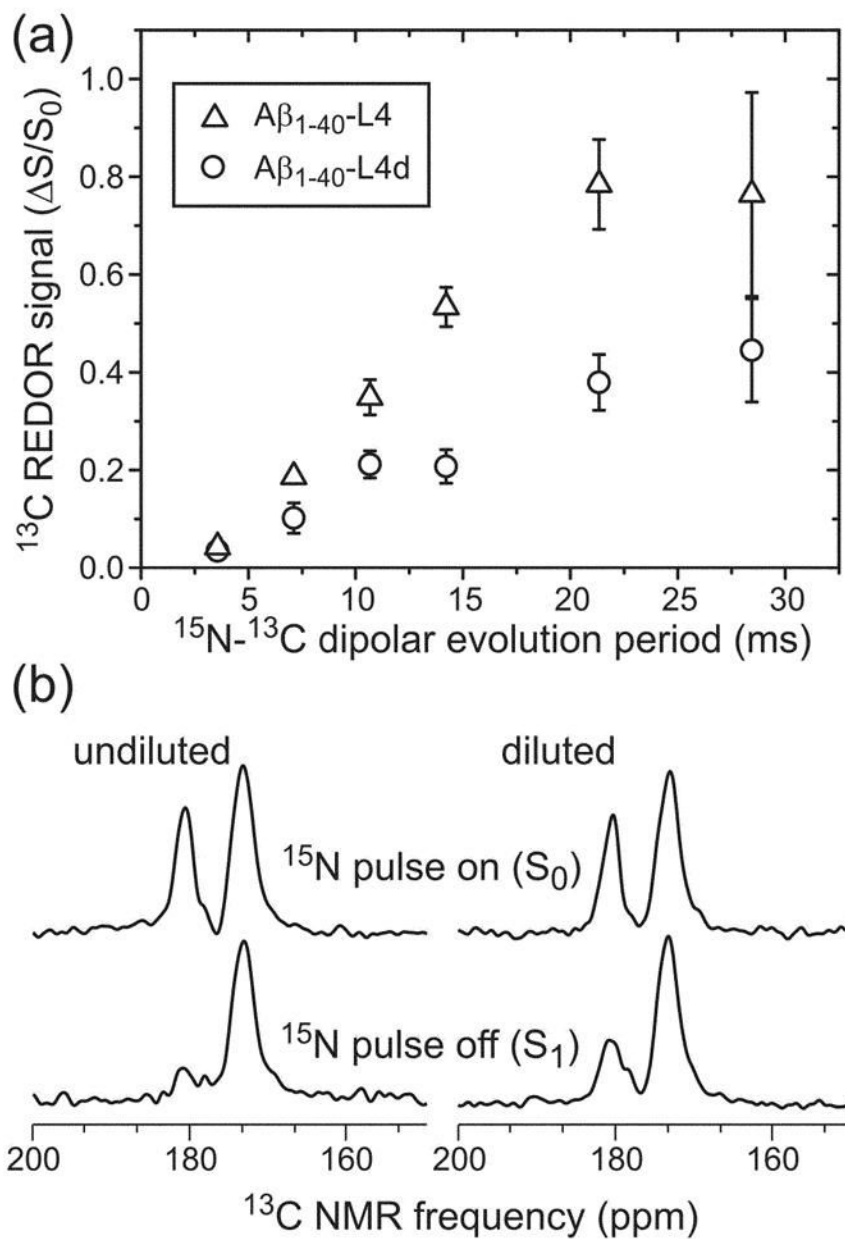


**Figure 2:**

(a) 2D solid state  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectrum of  $\text{A}\beta_{1-40}$ -L1 fibrils, recorded at 14.1 T with a 500 ms mixing period and 18.00 kHz MAS frequency. Strongest crosspeaks connect all NMR frequencies of a given  $^{13}\text{C}$ -labeled residue. Weaker crosspeaks connect NMR frequencies of  $^{13}\text{C}$ -labeled residues that make quaternary contacts or are sequential. (b) Expansion of aliphatic/aliphatic and aliphatic/aromatic regions. Solid lines trace resonance assignment paths for aliphatic  $^{13}\text{C}$  NMR frequencies of F19, I32, and V36. Dotted lines connect aliphatic frequencies of these residues to the aromatic  $^{13}\text{C}$  NMR signal of F19 at 129.5 ppm. Aliphatic/aromatic crosspeaks indicate F19/I32 and F19/V36 sidechain contacts. Red arrow points to an MAS sideband crosspeak of F19.



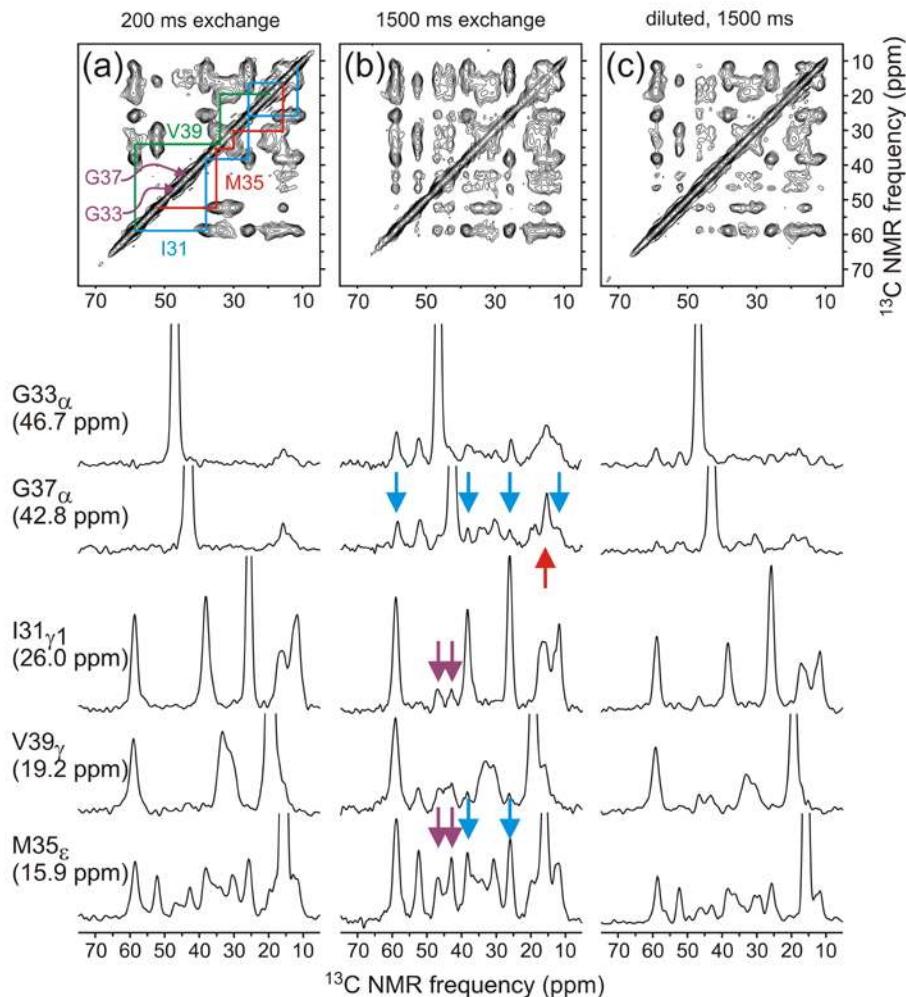
**Figure 3:** 1D slices of 2D solid state  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectra of the indicated  $\text{A}\beta_{1-40}$  fibril samples, taken at the indicated  $^{13}\text{C}$  NMR chemical shifts. Alignment of peaks in F19 or F20 aromatic slices with peaks in the  $\text{C}_\alpha$  slices of other  $^{13}\text{C}$ -labeled residues allows the identification of aliphatic/aromatic crosspeaks that indicate quaternary contacts. Parts (a) and (c) show the presence of F19/I32, F19/V36, and F19/L34 contacts. Parts (d) and (e) show the absence of F20/I32, F20/V36, and F20/I31 contacts. Part (b) demonstrates the effect of isotopic dilution on F19/I32 and F19/V36 contacts. Part (f) shows the presence of F20/I31 contacts in fibrils grown under quiescent conditions. Measurement conditions as in Fig. 2, with MAS frequencies of 18.00 kHz in (a), (b), and (d), 21.50 kHz in (c), and 16.60 kHz in (e) and (f). Peaks arising from MAS sidebands are indicated by "ss". Asterisks indicate peaks from the indicated residues, due either to partial overlap of  $^{13}\text{C}$  NMR lines or to crosspeaks between signals of sequential  $^{13}\text{C}$ -labeled residues.

**Figure 4:**

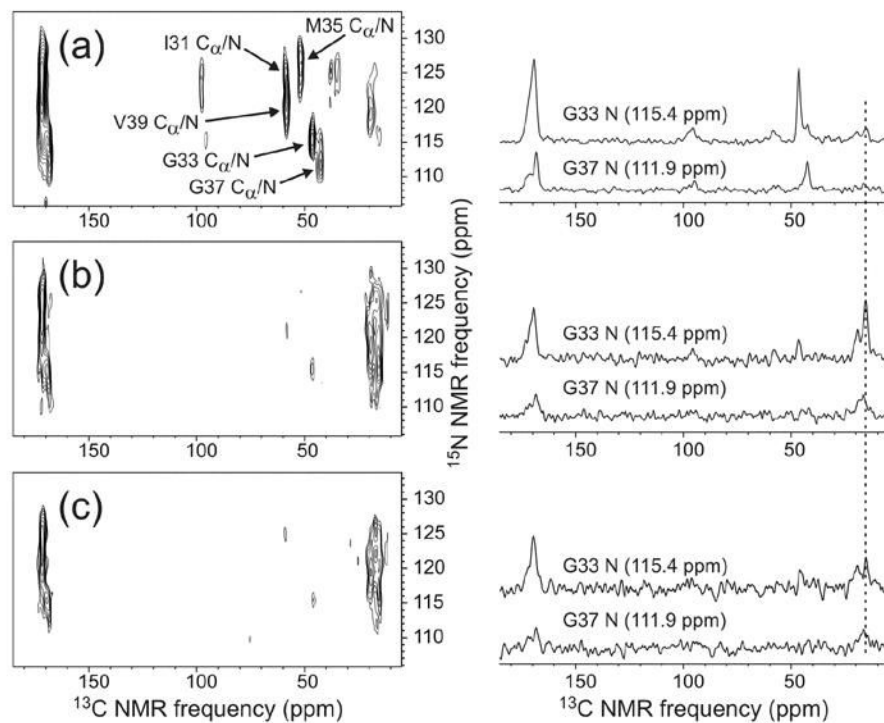
(a) Frequency-selective  $^{15}\text{N}$ - $^{13}\text{C}$  REDOR data for  $\text{A}\beta_{1-40}\text{-L4}$  (triangles) and  $\text{A}\beta_{1-40}\text{-L4d}$  (circles) fibrils, recorded at 14.1 T with a 9.00 kHz MAS frequency and with selective refocusing pulses near the NMR frequencies of D23  $\text{C}_\gamma$  and K28  $\text{N}_\zeta$ . The build-up of the normalized REDOR difference signal  $\Delta S/S_0$  for D23  $\text{C}_\gamma$  in  $\text{A}\beta_{1-40}\text{-L4}$  fibrils with increasing evolution period indicates an interatomic distance of roughly 3.7 Å between D23  $\text{C}_\gamma$  and K28  $\text{N}_\zeta$ . The lower asymptotic value of  $\Delta S/S_0$  for  $\text{A}\beta_{1-40}\text{-L4d}$  fibrils indicates that close contacts between D23  $\text{C}_\gamma$  and K28  $\text{N}_\zeta$  sites are primarily intermolecular. (b)  $S_0$  and  $S_1$  spectra from frequency-selective REDOR measurements at a 21.33 ms evolution period, obtained at 9.39 T, demonstrating the frequency selectivity and the effect of isotopic dilution. NMR lines at

180.8 ppm and 173 ppm are from D23 C $_{\gamma}$  and backbone carbonyl sites, respectively. S $_0$  and S $_1$  measurements differ only by a single selective  $^{15}\text{N}$  refocusing pulse, and  $\Delta S_0 - S_1$ .

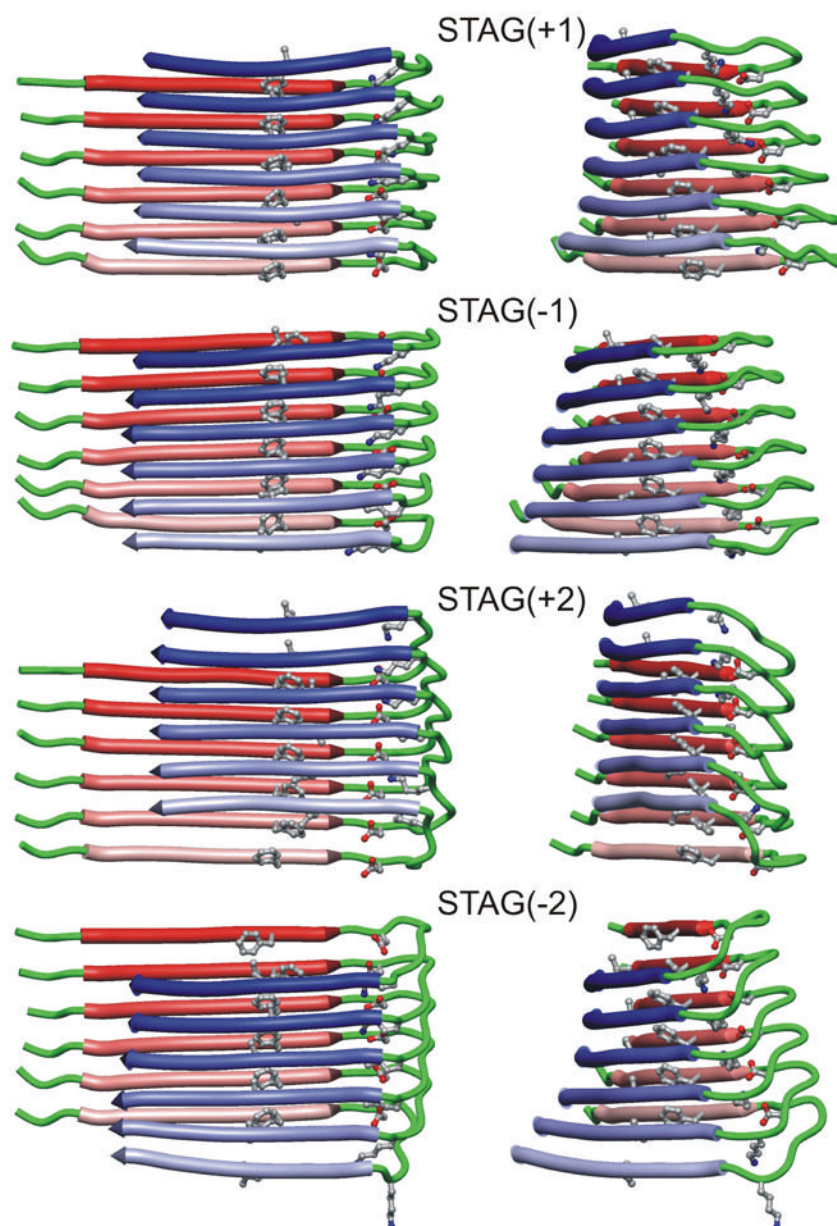




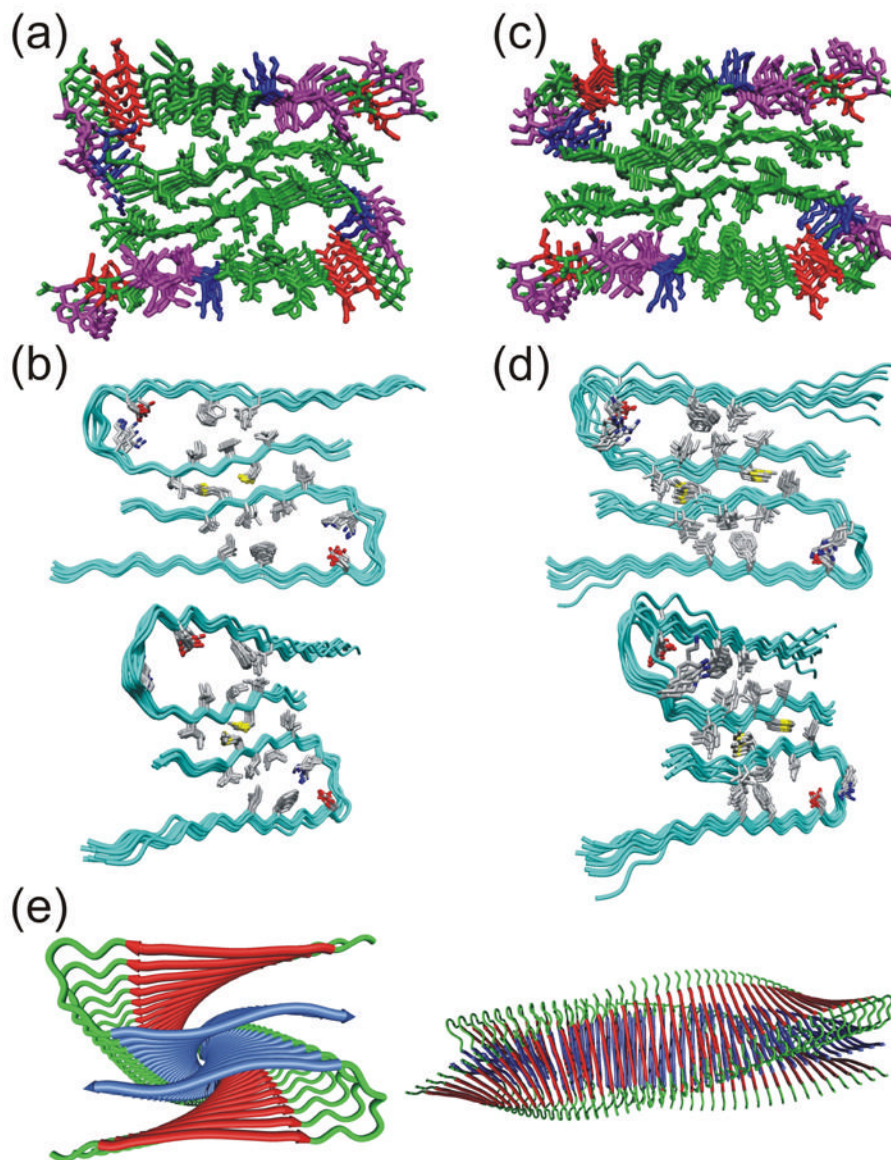
**Figure 5:** 2D solid state  $^{13}\text{C}$ - $^{13}\text{C}$  NMR spectra of  $\text{A}\beta_{1-40}\text{-L5}$  (a,b) and  $\text{A}\beta_{1-40}\text{-L5d}$  (c) fibrils, recorded at 14.1 T with a 23.50 kHz MAS frequency and indicated mixing periods. Resonance assignment pathways are shown in part (a). 1D slices at indicated NMR frequencies are shown beneath each 2D spectrum. Blue arrows indicate I31/G37 and I31/M35 inter-residue crosspeaks. Purple arrows indicate M35/G33 and M35/G37 crosspeaks. Red arrow indicates a G37/M35 crosspeak. Vertical scales are identical in all 1D slices in the same column.



**Figure 6:** 2D solid state  $^{15}\text{N}$ - $^{13}\text{C}$  NMR spectra of  $\text{A}\beta_{1-40}$ -L5 (a,b) and  $\text{A}\beta_{1-40}$ -L5d (c) fibrils, recorded at 14.T with a 11.14 kHz MAS frequency and TEDOR recoupling periods of 2.873 ms (a) or 5.745 (b,c). Assignments of one-bond  $^{13}\text{C}_\alpha/^{15}\text{N}$  crosspeaks are shown in part (a). 1D slices at the indicated  $^{15}\text{N}$  NMR frequencies are shown to the right of each 2D spectrum. Dashed line indicates the  $^{13}\text{C}$  NMR chemical shift of M35  $\text{C}_\alpha$ .



**Figure 7:** Four candidate models for the internal quaternary contacts within  $A\beta_{1-40}$  fibrils, with different degrees and directions of stagger. Sidechains of F19, D23, K28, and L34 are shown. Representations on the right are rotated by  $60^\circ$  about the z axis relative to those on the left.



**Figure 8:** Structural models for  $A\beta_{1-40}$  fibrils with F19/L34 internal quaternary contacts,  $C_{2z}$  symmetry, and either STAG(+2) stagger (a,b,e) or STAG(-2) stagger (c,d). Models were generated by a restrained molecular dynamics and restrained energy minimization protocol, applied to a dodecameric cluster of  $A\beta_{9-40}$  molecules, with all restraints being derived from solid state NMR measurements. Residues 1-8 are disordered, and were omitted from the modeling calculations. Parts (a) and (c) show averages of ten energy-minimized structures, as calculated by MOLMOL (73). Hydrophobic (G, A, F, V, L, I, M), negatively charged (D, E), positively charged (K), and polar (Y, H, Q, N, S) residues are colored green, red, blue, and magenta, respectively. Parts (b) and (d) show bundles of central pairs of molecules in ten energy-minimized structures. Sidechains of L17, F19, D23, K28, I31, I32, L34, M35, and V36 are shown. Upper view is along the z axis. Lower view is rotated by  $45^\circ$  about the y axis. Part (e) shows a cartoon representation of a full fibril, viewed parallel and perpendicular to z, generated from multiple copies of a central pair of molecules in part (a), with  $4.8 \text{ \AA}$  displacements along

z and an arbitrarily chosen twist of  $0.833^\circ/\text{\AA}$ . Atomic coordinates for parts (a)-(d) are available upon request (e-mail address: robertty@mail.nih.gov).



**Table 1:**Isotopic labeling of A $\beta$ <sub>1-40</sub> fibril samples

sample name	uniformly <sup>15</sup> N, <sup>13</sup> C-labeled residues	labeled fraction (%) <sup>a</sup>
A $\beta$ <sub>1-40</sub> -L1	K16, F19, A21, E22, I32, V36	100
A $\beta$ <sub>1-40</sub> -L1d	K16, F19, A21, E22, I32, V36	31
A $\beta$ <sub>1-40</sub> -L2	F19, V24, G25, A30, I31, L34, M35	100
A $\beta$ <sub>1-40</sub> -L3	F20, E22, K28, I32, M35, V36	100
A $\beta$ <sub>1-40</sub> -L4	F20, D23, V24, K28, G29, A30, I31	100
A $\beta$ <sub>1-40</sub> -L4d	F20, D23, V24, K28, G29, A30, I31	33
A $\beta$ <sub>1-40</sub> -L5	I31, G33, M35, G37, V39	100
A $\beta$ <sub>1-40</sub> -L5d	I31, G33, M35, G37, V39	33

<sup>a</sup> Mole fraction of labeled peptide molecules when fibrils were grown from a mixture of labeled and unlabeled molecules. Labeled molecules have >95% isotopic enrichment at all nitrogen and carbon sites of the indicated residues. Unlabeled molecules have natural-abundance levels of <sup>15</sup>N and <sup>13</sup>C.