

# Rapid distinction of intracellular and extracellular proteins using NMR diffusion measurements

Christopher A. Waudby<sup>1</sup>, Mick D. Mantle<sup>2</sup>, Lisa D. Cabrita<sup>1</sup>, Lynn F. Gladden<sup>2</sup>, Christopher M. Dobson<sup>3</sup> and John Christodoulou<sup>1,\*</sup>

<sup>1</sup>Institute of Structural and Molecular Biology, University College London and Birkbeck College, Gower Street, London WC1E 6BT, UK

<sup>2</sup>Department of Chemical Engineering and Biotechnology, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, UK

<sup>3</sup>Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge CB2 1EW, UK

Supporting Information Placeholder

**ABSTRACT:** In-cell NMR spectroscopy offers a unique opportunity to begin to investigate the structures, dynamics and interactions of molecules within their functional environments. An essential aspect of this technique is to define whether or not observed signals are attributable to intracellular species rather than components of the extracellular medium. We report here the results of NMR measurements of the diffusion behavior of proteins expressed within bacterial cells, and find that these experiments provide a rapid and non-destructive probe of localization within cells and can be used to determine the size of the confining compartment. We show that diffusion can also be exploited as an editing method to eliminate extracellular species from high-resolution multi-dimensional spectra, and should be applicable to a wide range of problems. This approach is demonstrated here for a number of protein systems, using both <sup>15</sup>N and <sup>13</sup>C (methyl-TROSY) based acquisition.

NMR spectroscopy, in conjunction with specific isotope labeling methods, is a powerful approach for the direct observation of molecules such as proteins within their natural and highly complex cellular environments, as well as in the dilute solutions commonly studied under laboratory conditions. In recent years, for example, a number of studies have succeeded in characterizing at the atomic level the structures and properties of proteins within cells<sup>1,2</sup>. A fundamental requirement of all in-cell NMR studies is to determine unequivocally whether or not specific resonances in a given spectrum originate from species that are localized within the cell rather than in the extracellular medium. As in most cases the chemical shifts of intracellular and extracellular species are likely to be very similar, this exercise is in general non-trivial; indeed, the most common approach at present is simply to centrifuge the sample and to compare spectra of the supernatant with those from the original sample<sup>3</sup>. A non-destructive alternative is highly desirable, and we report here a simple approach based on pulsed-field gradient NMR diffusion measurements that can provide the required information in a very short time, typically less than two minutes.

NMR spectroscopy using pulsed-field gradients provides a powerful method for the characterization of molecular diffu-

sion<sup>4</sup>, and for example has been applied to study the diffusion of proteins within cell lysates and other crowded solutions in an effort to develop an understanding of the physical processes controlling macromolecular transport within the cell<sup>5</sup>. Diffusion may also be used as a means of spectral editing, e.g. to suppress the resonances of small molecule metabolites from spectra of macromolecules within cell lysates<sup>6</sup>. However, within intact cells the measurement of protein diffusion has been dominated by a range of fluorescence methods<sup>7,8</sup>. Such measurements have demonstrated that the effective viscosity of the eukaryotic cytosol is typically 3–4 times greater than that of water<sup>9</sup>, while in the highly crowded bacterial cytosol, containing 300–400 mg mL<sup>-1</sup> of macromolecules<sup>10</sup>, translational diffusion of proteins is reduced by approximately an order of magnitude relative to dilute aqueous solution<sup>11</sup>.

An essential difference between in-cell studies and conventional solution studies is that the diffusion of any molecule under observation is restricted to a much smaller volume, by being confined within a cell or a cellular compartment. In the specific case of *E. coli*, the system studied in this paper, the total cellular volume corresponds to approximately 0.5 fL. On the timescale of NMR diffusion measurements, the consequence of this confinement will be a reduction in the apparent diffusion coefficient, suggesting that diffusion-edited NMR experiments could be used to distinguish between intracellular and extracellular species.

In this communication, we first explore this approach using the intrinsically disordered protein  $\alpha$ -synuclein ( $\alpha$ Syn), which has previously been reported to give well-resolved NMR resonances when expressed within *E. coli* cells<sup>12</sup>. <sup>15</sup>N-edited stimulated-echo (STE) diffusion experiments<sup>13</sup> of such samples were recorded here using a long diffusion delay,  $\Delta$ , of 300 ms, in order to maximize the contrast between slowly and rapidly diffusing species. The signal intensities  $I(G)$  for a sample of cells expressing  $\alpha$ Syn, and for purified  $\alpha$ Syn added separately to the extracellular medium of a sample of cells, are plotted in Fig. 1A, and are fitted to the Stejskal-Tanner equation<sup>14</sup> to determine the apparent diffusion coefficient,  $D_{app}$ :

$$I(G) = I(0) \exp[-\gamma^2 G^2 \delta^2 s^2 (\Delta - \delta/3 - \tau/2) D_{app}] \quad (1)$$

where  $I(0)$  is the signal intensity in the absence of gradients,  $\gamma$  is the magnetogyric ratio of the proton,  $\delta$  is the gradient pulse

length,  $s$  is the gradient shape factor,  $\tau$  is the delay between bipolar gradients, and  $G$  is the gradient strength.

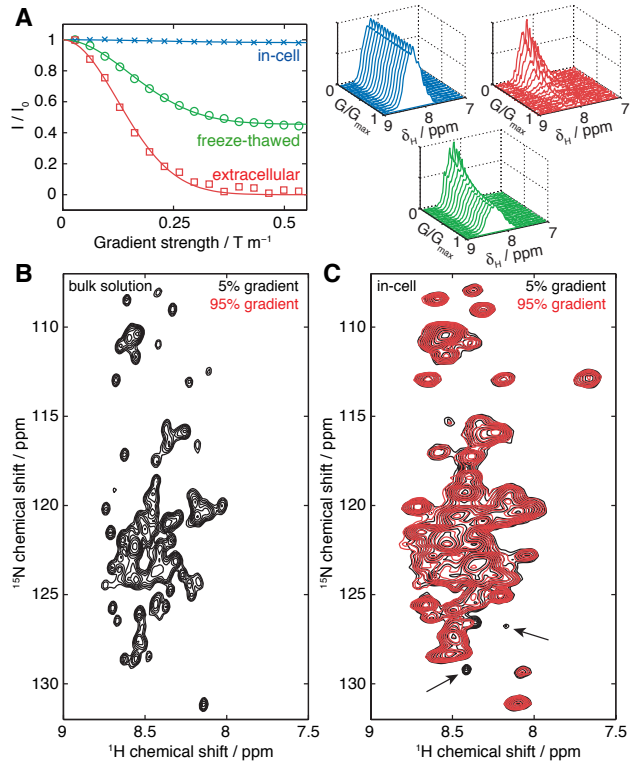


Figure 1. (A) 300 ms  $^{15}\text{N}$ -edited XSTE diffusion NMR measurements<sup>13</sup> of cells in which  $\alpha\text{Syn}$  has been expressed (blue), cells partially lysed following freeze-thawing with liquid  $\text{N}_2$  (green), and purified  $\alpha\text{Syn}$  added to the extracellular medium of a sample of cells (red). (B, C) Diffusion-edited (300 ms XSTE) HSQC NMR spectra<sup>15</sup> of (B) purified  $\alpha\text{Syn}$  in bulk solution, and (C) cells expressing  $\alpha\text{Syn}$ . The gradient strength used in each experiment is indicated relative to the maximum accessible gradient strength of  $0.55 \text{ T m}^{-1}$ . Arrows highlight resonances of extracellular species that are absent at higher gradient strengths.

The intensity of the resonances of cell samples at the maximum gradient strength applied here,  $G = 0.55 \text{ T m}^{-1}$ , was observed to be  $97 \pm 1 \%$  of that in the absence of the gradient, with a fitted value of  $D_{\text{app}} = 4.6 \pm 0.8 \times 10^{-13} \text{ m}^2 \text{ s}^{-1}$ . By contrast, resonances from exogenous  $\alpha\text{Syn}$  are effectively completely attenuated at this maximum gradient strength. The measured value of  $D = (1.2 \pm 0.1) \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$  is only slightly reduced relative to that observed for  $\alpha\text{Syn}$  in bulk solution,  $D = (1.3 \pm 0.1) \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ , which is itself comparable to values from previous measurements and corresponds to a hydrodynamic radius of  $25 \pm 2 \text{ \AA}$ <sup>16</sup>. This result reveals that intracellular and extracellular protein molecules can be distinguished clearly as their apparent diffusion coefficients differ by almost three orders of magnitude. Each experiment in the present study was acquired within six minutes, and this time could be reduced to under a minute by omitting intermediate gradient points.

The large difference in the apparent diffusion coefficients for a protein inside and outside the cell provides an opportunity to use pulsed-field gradients to dephase selectively the resonances of rapidly diffusing extracellular species and so to use diffusion-edited experiments to observe intracellular species exclusively. This strategy is illustrated in Fig. 1B,C, where

diffusion-edited HSQC spectra<sup>15</sup> have been recorded of purified  $\alpha\text{Syn}$  in bulk solution (Fig. 1B) and of  $\alpha\text{Syn}$  expressed within *E. coli* cells (Fig. 1C). The sensitivity of these measurements was found to be approximately 40% of that of a conventional HSQC experiment, due in part to an increase in relaxation that occurs during the longer pulse sequence, but predominantly to the 50% loss of signal inherent in all stimulated echo experiments, as only a single transverse magnetization component can be stored longitudinally during the diffusion delay.

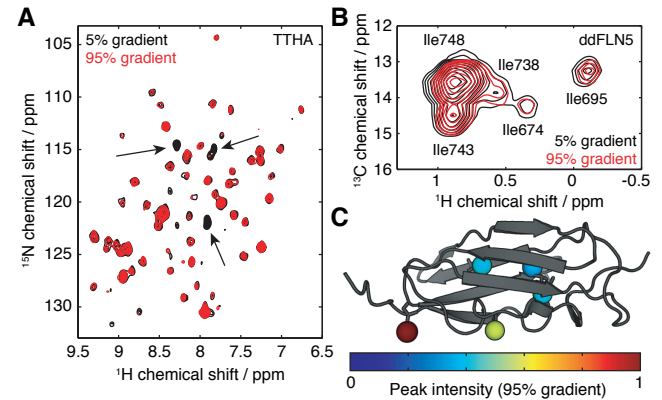


Figure 2. (A) Diffusion-edited (300 ms  $^{15}\text{N}$  XSTE) HSQC NMR spectra of TTHA expressed within cells. The gradient strength used in each experiment is indicated relative to the maximum accessible gradient strength of  $0.55 \text{ T m}^{-1}$ . Arrows highlight resonances of extracellular species that are absent at higher gradient strengths. (B) Diffusion-edited (300 ms STE)  $^{13}\text{C}$  HMQC (methyl-TROSY) NMR spectra of  $[\text{Ile-}^{13}\text{CH}_3]\text{-ddFLN5}$  expressed within cells. (C) Crystal structure of ddFLN5 (pdb 1QFH) showing isoleucine  $\text{C}\delta$  groups, colored according to the peak intensity observed within the cell.

To validate further this approach, additional in-cell samples were prepared and subjected to partial lysis induced by freeze-thawing with liquid  $\text{N}_2$ . The maximum attenuation of the stimulated echo was observed to be  $55 \pm 2 \%$  (Fig. 1A), indicating that approximately half of the protein had escaped from the cell. This value compares to  $51 \pm 1 \%$  determined from analysis of the supernatant following centrifugation and shows the NMR method to be highly robust, at least for the bacterial cells studied in this communication.

We have also investigated the application of diffusion-edited methods to the observation of two representative folded proteins expressed within the cell. TTHA1718 ('TTHA') is a 66-residue folded protein that has been shown to give well-resolved HSQC spectra when expressed within the cell<sup>2</sup>. We find here that well-resolved diffusion-edited HSQC spectra may also be acquired for such samples (Fig. 2A). As was the case for  $\alpha\text{Syn}$ , a number of resonances are absent at higher gradient strengths and therefore can be attributed to extracellular species (Fig. 2A, arrows). However, in our hands we also found that TTHA samples showed higher levels of leakage than was typically observed for  $\alpha\text{Syn}$ : the signal intensity at the maximum gradient strength was  $81 \pm 3 \%$  of that in the absence of the gradient, indicating that approximately 19% of the protein was present outside the cell in this experiment. In such circumstances, diffusion-edited acquisition is particularly valuable in permitting the exclusive observation of intracellular species.

The second folded protein we examined is ddFLN5, a 113-residue immunoglobulin domain from the *Dictyostelium discoideum* gelation factor ABP-120, currently under study within our group as a ribosome-nascent chain complex for the investigation of cotranslational folding<sup>17,18</sup>. However, in contrast to the smaller TTHA molecule, resonances of ddFLN5 could not be observed in <sup>1</sup>H-<sup>15</sup>N HSQC spectra of cell samples (Fig. S1), indicating the presence of rapid transverse relaxation that may result from the viscosity of the cytosol, and also potentially from specific or non-specific interactions with other components of the cell<sup>19</sup>. We therefore prepared deuterated cell samples with selective <sup>13</sup>CH<sub>3</sub> labeling of isoleucine C $\delta$  methyl groups, in order to utilize the methyl-TROSY effect to reduce the effect of transverse relaxation<sup>20</sup>. Methyl-TROSY methods were also combined with STE diffusion measurements<sup>21</sup> which, as illustrated for  $\alpha$ Syn, may be acquired rapidly in a 1D manner to measure echo attenuations. In addition, diffusion-edited <sup>1</sup>H-<sup>13</sup>C HMQC spectra were acquired, and are shown in Fig. 2B for a sample of cells in which isoleucine-labeled ddFLN5 has been expressed. All ddFLN5 isoleucine resonances were observed, with identical chemical shifts as observed for the protein in bulk solution (Fig. S2) indicating that no major structural changes have occurred within the cell. Peak intensities at the maximum gradient strength were  $83 \pm 2$  % of those in the absence of the gradient, indicating that approximately 17% of the protein was present outside of the cell.

Significant residue-to-residue variation was observed in the intensities of resonances in the diffusion-edited spectrum of ddFLN5 (Fig. 2B). By contrast, intensities in the spectrum of the protein in bulk solution are close to uniform (Fig. S2). To investigate this broadening effect further, the relative peak intensities were projected onto the structure of the protein (Fig. 2C), from which it may be observed that the greatest intensities in the diffusion-edited spectrum are found for residues on the surface of the protein. The intensities are inversely correlated with predicted methyl  $S^2$  order parameters<sup>22</sup> ( $r^2 = 0.90$ , Fig. S3) and, given the slow rotational diffusion within the crowded cytosol, this suggests that the extent of local mobility on ps–ns timescales may be an important factor in determining the observability of intracellular material. However, interactions between the protonated methyl groups within the core of the protein might also contribute significantly to the observed relaxation. Future work, combining diffusion-edited acquisition with spin relaxation measurements, has the potential to enable these effects to be interpreted in more detail.

The apparent diffusion coefficient determined by NMR measurements is related to the mean square displacement during the diffusion delay,  $D_{\text{app}} = \langle Z^2 \rangle / 2\Delta$ . For an intracellular species,  $\langle Z^2 \rangle$  is limited by the size of the cell, and the apparent diffusion coefficient may therefore provide information on the size of the confining compartment. To investigate the possibility of obtaining such information, in a further series of experiments we recorded a series of diffusion measurements using a probe (Bruker Diff30) that is able to provide a gradient strength of up to  $11.7 \text{ T m}^{-1}$ .

This approach provided larger echo attenuations, allowing the determination of the apparent diffusion coefficients of intracellular  $\alpha$ Syn. <sup>1</sup>H spin-echo experiments were recorded for four values of  $\Delta$  from 11 to 20 ms, and echo attenuations of up to 90% were observed in all cases (Fig. 3). These attenuations were independent of  $\Delta$ , indicating that diffusion is restricted, and fitting the data to Eq. 1 indicates RMS displace-

ments of  $0.33 \pm 0.02 \mu\text{m}$  (Fig. 3, inset). This is comparable in magnitude to an RMS displacement of  $0.47 \mu\text{m}$  estimated from Brownian dynamics simulations<sup>23</sup> for a compartment size of  $0.5 \times 0.5 \times 2 \mu\text{m}$ , typical for an *E. coli* cell. Thus, the characterization of restricted diffusion provides not only the ability to quantify intracellular localization, but also to provide an estimate of the size of the confining compartment. We note that we do not observe diffusion-diffraction effects in these measurements, for example, as previously observed for water diffusing in red blood cells<sup>24</sup>. This finding may reflect a combination of heterogeneity in the cell size and lack of alignment within the sample, and spatial averaging occurring during the finite gradient pulse length, resulting in shallower diffraction minima<sup>25</sup>.

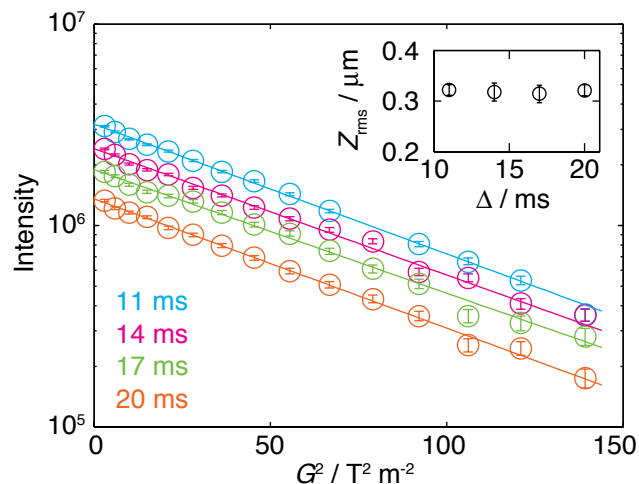


Figure 3. <sup>1</sup>H spin-echo measurements ( $\delta=2$  ms) of an in-cell sample of  $\alpha$ Syn, with the diffusion time,  $\Delta$ , varied between 11 and 20 ms as indicated. Data are fitted to Eq. 1, and (inset) the RMS displacements,  $Z_{\text{rms}} = (2D_{\text{app}}\Delta)^{1/2}$ , are plotted as a function of  $\Delta$ .

Finally, we consider the role of diffusion measurements in the study of other types of cells. The diffusion-editing methodology described in this communication is particularly effective due to the effect of restricted dimensions on the apparent diffusion coefficient. However, the magnitude of this enhancement decreases when the cell size becomes comparable to the RMS displacement occurring during the diffusion measurement, and simple estimates suggest that the effects described here for *E. coli* cells are not likely to be significant at length scales of  $10 \mu\text{m}$  and above – e.g. for mammalian cells and particularly for *X. laevis* oocytes used previously for in-cell NMR studies<sup>26,27</sup>. However, it should remain possible to distinguish intracellular and extracellular species via the slower diffusion in the cytoplasm. More importantly, restricted diffusion is likely to be a key probe for observing the confinement of species to compartments or organelles within the cell.

In summary, diffusion measurements are a powerful component of the biomolecular NMR toolkit, with diverse applications including the study of protein aggregation<sup>28,29</sup> and large macromolecular complexes such as the ribosome and ribosome nascent chain complexes<sup>17,30</sup>. We have shown in this communication that diffusion experiments also provide a means of rigorously identifying and selectively observing protein molecules within the living cell. We believe that such

methods are widely applicable, and are able to provide important information in the emerging field of in-cell NMR.

## ASSOCIATED CONTENT

Materials and methods and supplementary figures. This material is available free of charge via the Internet at <http://pubs.acs.org>.

## AUTHOR INFORMATION

### Corresponding Author

\* [j.christodoulou@ucl.ac.uk](mailto:j.christodoulou@ucl.ac.uk)

### Notes

The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

We thank Dr John Kirkpatrick for valuable advice with the NMR experiments. This work was supported by the BBSRC (C.A.W., J.C.), the Wellcome Trust (C.M.D.) and HFSP (J.C.). M.D.M. and L.F.G. wish to thank the UK EPSRC for funding under Grant EP/F047991/1.

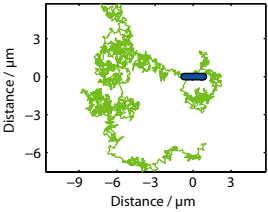
## ABBREVIATIONS

$\alpha$ Syn,  $\alpha$ -synuclein; STE, stimulated echo.

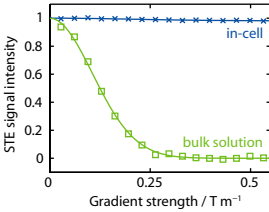
## REFERENCES

- (1) Serber, Z.; Keatinge-Clay, A. T.; Ledwidge, R.; Kelly, A. E.; Miller, S. M.; Dötsch, V. *J Am Chem Soc* **2001**, *123*, 2446–2447.
- (2) Sakakibara, D.; Sasaki, A.; Ikeya, T.; Hamatsu, J.; Hanashima, T.; Mishima, M.; Yoshimasu, M.; Hayashi, N.; Mikawa, T.; Wälchli, M.; Smith, B. O.; Shirakawa, M.; Güntert, P.; Ito, Y. *Nature* **2009**, *458*, 102–105.
- (3) Barnes, C. O.; Pielak, G. J. *Proteins* **2011**, *79*, 347–351.
- (4) Callaghan, P. T. *Translational Dynamics and Magnetic Resonance: Principles of Pulsed Gradient Spin Echo NMR*; Oxford University Press, **2011**.
- (5) Li, C.; Wang, Y.; Pielak, G. J. *J Phys Chem B* **2009**, *113*, 13390–13392.
- (6) Rajagopalan, S.; Chow, C.; Raghunathan, V.; Fry, C. G.; Cavagnero, S. *J Biomol NMR* **2004**, *29*, 505–516.
- (7) Verkman, A. S. *Meth Enzymol* **2003**, *360*, 635–648.
- (8) Bacia, K.; Kim, S. A.; Schwille, P. *Nat Methods* **2006**, *3*, 83–89.
- (9) Dix, J. A.; Verkman, A. S. *Annual review of biophysics* **2008**, *37*, 247–263.
- (10) Zimmerman, S. B.; Trach, S. O. *J Mol Biol* **1991**, *222*, 599–620.
- (11) Elowitz, M. B.; Surette, M. G.; Wolf, P. E.; Stock, J. B.; Leibler, S. *J Bacteriol* **1999**, *181*, 197–203.
- (12) Li, C.; Charlton, L. M.; Lakkavaram, A.; Seagle, C.; Wang, G.; Young, G. B.; Macdonald, J. M.; Pielak, G. J. *J Am Chem Soc* **2008**, *130*, 6310–6311.
- (13) Ferrage, F.; Zoonens, M.; Warschawski, D. E.; Popot, J.-L.; Bodenhausen, G. *J Am Chem Soc* **2003**, *125*, 2541–2545.
- (14) Wu, D.; Chen, A.; Johnson, C. *J Magn Reson Ser A* **1995**, *115*, 260–264.
- (15) Augustyniak, R.; Ferrage, F.; Paquin, R.; Lequin, O.; Bodenhausen, G. *J Biomol NMR* **2011**, *50*, 209–218.
- (16) Dedmon, M. M.; Lindorff-Larsen, K.; Christodoulou, J.; Vendruscolo, M.; Dobson, C. M. *J Am Chem Soc* **2005**, *127*, 476–477.
- (17) Hsu, S.-T. D.; Fucini, P.; Cabrita, L. D.; Launay, H.; Dobson, C. M.; Christodoulou, J. *Proc Natl Acad Sci USA* **2007**, *104*, 16516–16521.
- (18) Hsu, S.-T. D.; Cabrita, L. D.; Christodoulou, J.; Dobson, C. M. *Biomol NMR Assign* **2009**, *3*, 29–31.
- (19) Barnes, C. O.; Monteith, W. B.; Pielak, G. J. *Chembiochem* **2011**, *12*, 390–391.
- (20) Tugarinov, V.; Hwang, P. M.; Ollerenshaw, J. E.; Kay, L. E. *J Am Chem Soc* **2003**, *125*, 10420–10428.
- (21) Didenko, T.; Boelens, R.; Rüdiger, S. G. D. *Protein Eng Des Sel* **2011**, *24*, 99–103.
- (22) Ming, D.; Brüschweiler, R. *J Biomol NMR* **2004**, *29*, 363–368.
- (23) Waudby, C. A.; Christodoulou, J. *J Magn Reson* **2011**, *211*, 67–73.
- (24) Kuchel, P. W.; Coy, A.; Stilbs, P. *Magn Reson Med* **1997**, *37*, 637–643.
- (25) Mitra, P.; Halperin, B. *J Magn Reson Ser A* **1995**, *113*, 94–101.
- (26) Selenko, P.; Wagner, G. *J Struct Biol* **2007**, *158*, 244–253.
- (27) Inomata, K.; Ohno, A.; Tochio, H.; Isogai, S.; Tenno, T.; Nakase, I.; Takeuchi, T.; Futaki, S.; Ito, Y.; Hiroaki, H.; Shirakawa, M. *Nature* **2009**, *458*, 106–U11.
- (28) Baldwin, A. J.; Anthony-Cahill, S. J.; Knowles, T. P. J.; Lippens, G.; Christodoulou, J.; Barker, P. D.; Dobson, C. M. *Angew Chem Int Edit* **2008**, *47*, 3385–3387.
- (29) Waudby, C. A.; Knowles, T. P. J.; Devlin, G. L.; Skepper, J. N.; Ecrolyd, H.; Carver, J. A.; Welland, M. E.; Christodoulou, J.; Dobson, C. M.; Meehan, S. *Biophys J* **2010**, *98*, 843–851.
- (30) Christodoulou, J.; Larsson, G.; Fucini, P.; Connell, S. R.; Pertinhez, T. A.; Hanson, C. L.; Redfield, C.; Nierhaus, K. H.; Robinson, C. V.; Schleucher, J.; Dobson, C. M. *Proc Natl Acad Sci USA* **2004**, *101*, 10949–10954.

Graphical abstract:



Slow and restricted protein diffusion within the cell



Distinction of intracellular and extracellular species using NMR diffusion measurements

# Supporting Information: Rapid distinction of intracellular and extracellular proteins using NMR diffusion measurements

Christopher A. Waudby<sup>1</sup>, Mick D. Mantle<sup>2</sup>, Lisa D. Cabrita<sup>1</sup>, Lynn F. Gladden<sup>2</sup>, Christopher M. Dobson<sup>3</sup> and John Christodoulou<sup>1</sup>

<sup>1</sup>*Institute of Structural and Molecular Biology, University College London and Birkbeck College, Gower Street, London WC1E 6BT, UK*

<sup>2</sup>*Department of Chemical Engineering and Biotechnology, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, UK*

<sup>3</sup>*Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge CB2 1EW, UK*

## Materials and Methods

### Sample preparation

The preparation of NMR samples of cells in which  $\alpha$ Syn, TTHA or ddFLN5 had been expressed followed previously described protocols<sup>1</sup>. 100 mL of LB was inoculated with BL21 (DE3) Gold cells (Stratagene) and incubated at 310 K with shaking (200 rpm) until an OD<sub>600</sub> of 0.6. Cells were harvested by centrifugation (1800 x g, 15 min, 277 K) and were resuspended in 50 mL of M9 minimal media containing 0.1% (w/v) <sup>15</sup>NH<sub>4</sub>Cl as the sole nitrogen source. After incubating for a 10 min recovery period at 310 K with shaking (200 rpm), expression was induced with 1 mM IPTG for 4 hrs. Cells were then harvested by centrifugation (1800 x g, 15 min, 277 K), resuspended in 50 mL of M9 minimal media containing unlabelled NH<sub>4</sub>Cl to reduce background labelling, then harvested again by centrifugation. The cell pellet was resuspended as a 40% (v/v) slurry in unlabelled M9 media containing 10% D<sub>2</sub>O and 0.001% DSS, and 600  $\mu$ L was transferred into a pre-shimmed NMR tube.

Lysed samples were prepared from NMR samples for which the initial cell integrity had been verified, by the methods described in this work, to be at least 98%. Samples were lysed by plunging the sample in a 1.5 mL Eppendorf tube into liquid N<sub>2</sub> and subsequently thawing at room temperature. Following NMR observations the sample was centrifuged (2000 x g, 10 min, 277 K), and the supernatant was removed for repeated observation by NMR, to determine the extent of lysis.

ddFLN5, with selective <sup>13</sup>CH<sub>3</sub> labeling of the isoleucine amino acid residues, was produced in BL21 (DE3) Gold E. coli cells (Stratagene). Cells were initially adapted in 99.9% <sup>2</sup>H<sub>2</sub>O M9 minimal media containing <sup>12</sup>C-d<sub>7</sub>-glucose, using a stepwise approach in order to maintain the growth kinetics of *E. coli*. The resulting culture was used to inoculate 100 mL of 99.9% <sup>2</sup>H<sub>2</sub>O M9

minimal media with  $^{12}\text{C}$ -d<sub>7</sub>-glucose (2 g/L) as the sole carbon source, and the cells were incubated at 37°C. At mid-log phase, 8 mg of the isoleucine precursor, 2-ketobutyric acid-4- $^{13}\text{C}$ -3,3-d<sub>2</sub> was added and the cells were allowed to recover for one hour. Following induction with 1 mM IPTG, expression proceeded for 4 hours and the cells were then prepared immediately for NMR analysis as for  $\alpha\text{Syn}$ . Following NMR observations, cells were harvested and lysed by sonication. ddFLN5, containing a hexa-histidine tag, was then purified by immobilized metal affinity chromatography using standard protocols. Briefly, the lysate was bound to Ni-NTA agarose (Qiagen), washed with 25 mM imidazole, and eluted with 250 mM imidazole before dialysis and storage in H<sub>2</sub>O at -80°C.

### NMR spectroscopy

NMR data were acquired at 16.4 T on a Bruker Avance III spectrometer equipped with a TXI cryoprobe, with a unidirectional gradient coil generating a maximum gradient of 0.55 T m<sup>-1</sup>.  $^{15}\text{N}$ -edited diffusion NMR experiments were measured at 310 K using a 300 ms  $^1\text{H}$  stimulated echo with storage as longitudinal magnetisation on  $^{15}\text{N}$  during the diffusion delay<sup>2</sup>. Bipolar trapezoidal gradient pulses (shape factor  $s = 0.9$ ) were applied with a total pulse length,  $\delta$ , of 4 ms and a spacing,  $\tau$ , of 200  $\mu\text{s}$ . Echos were acquired in 16 scans at 16 gradient strengths ranging linearly from 5 to 95% of the maximum gradient, with a total acquisition time of 6 min.  $^{13}\text{C}$ -edited diffusion measurements<sup>3</sup> were acquired using a 300 ms stimulated echo and bipolar trapezoidal gradient pulses with a total length,  $\delta$ , of 4 ms and a spacing,  $\tau$ , of 200  $\mu\text{s}$ . Echos were acquired in 64 scans at 8 gradient strengths ranging linearly from 5 to 95% of the maximum gradient, with a total acquisition time of 12 min.

NMR data were processed in nmrPipe<sup>4</sup> with a linear baseline, and the entire amide envelope was extracted and integrated. Data were fitted to the Stejskal-Tanner equation (Eq. 1, main text) or, for the analysis of partially lysed samples, a two-component model representing the attenuation due to diffusion of extracellular species, and a constant term representing intracellular species, the intensity of which did not decay with the gradient strengths used here:

$$I(G) = I_{\text{extracellular}} \exp[-\gamma^2 G^2 \delta^2 s^2 (\Delta - \delta/3 - \tau/2) D_{\text{app}}] + I_{\text{intracellular}} \quad (1)$$

Diffusion-edited  $^1\text{H}$ - $^{15}\text{N}$  HSQC spectra (using the XSTE-3D experiment<sup>5</sup>, adapted for one-dimensional gradient probes) were acquired at 277 K with a 300 ms stimulated echo and bipolar trapezoidal gradient pulses of length,  $\delta$ , of 4 ms. Two spectra were acquired, in an interleaved manner, having gradient strengths of 5 and 95% of the maximum. Diffusion-edited  $^1\text{H}$ - $^{13}\text{C}$  HMQC spectra<sup>3</sup> were also acquired using a 300 ms stimulated echo and bipolar trapezoidal gradient pulses

with a total length  $\delta$  of 4 ms, with gradient strengths 5 and 95% of the maximum.  $^1\text{H}$ - $^{13}\text{C}$  HMQC spectra of purified ddFLN5 were acquired using identical parameters.

NMR experiments utilizing high gradient strengths were acquired at 7.1 T on a Bruker DMX spectrometer equipped with a Diff30 probe, which provided a maximum gradient strength of 11.7 T  $\text{m}^{-1}$ . All measurements were performed at 310 K, using  $^1\text{H}$  spin-echos with trapezoidal gradients having a 0.1 ms ramp time. A comparison with uninduced cells showed that the methyl resonance at 0.7 ppm provided excellent selectivity for  $\alpha\text{Syn}$ , hence this signal was integrated for further analysis. Spectra were individually phased and baseline corrected.  $^1\text{H}$  spin-echo experiments were acquired with a gradient pulse length of 2 ms and the diffusion time,  $\Delta$ , varied from 11 to 20 ms. Each experiment was recorded at 16 linearly-spaced gradient strengths, with 32 scans acquired at each gradient point, and data were fitted to Eq. 1 (with  $\tau = 0$  as bipolar gradients were not used) to determine the apparent RMS displacement,  $Z_{\text{rms}} = (2D_{\text{app}}\Delta)^{1/2}$ .

### Brownian dynamics simulations

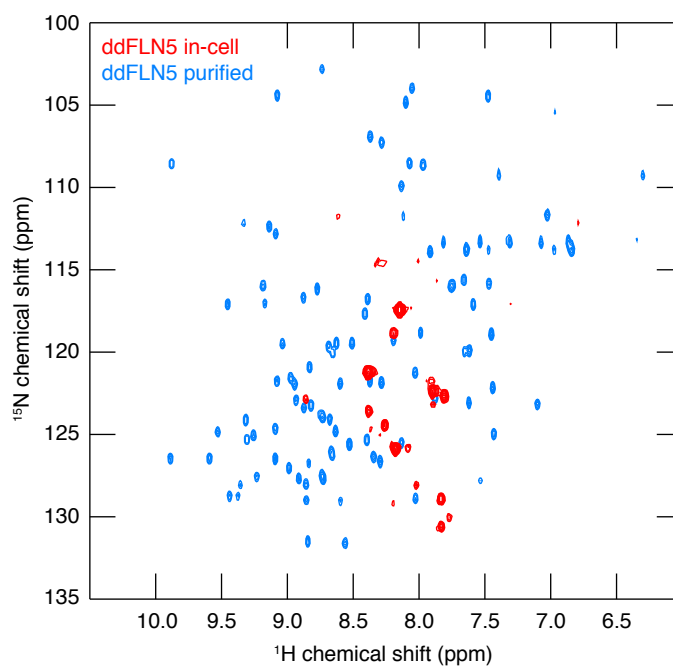
Monte Carlo simulations of diffusion were performed as previously described<sup>6</sup>, using a standard geometry for an *E. coli* cell, i.e. a cylinder with hemispherical caps at both ends having maximum dimensions of 0.5 x 0.5 x 2  $\mu\text{m}$ .

### References

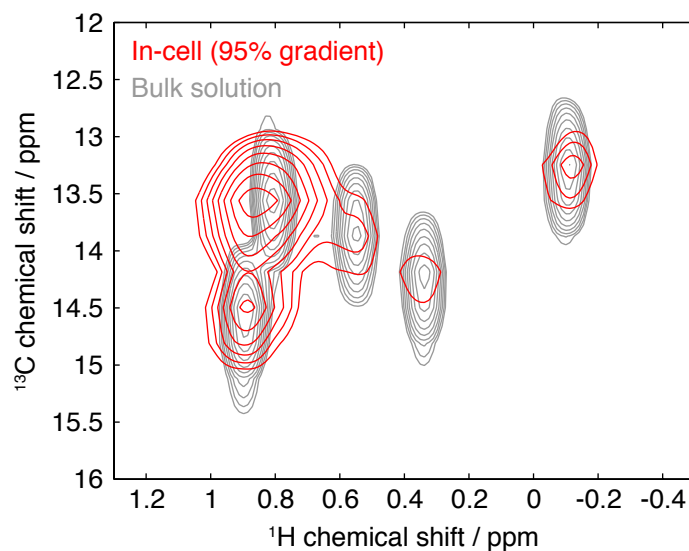
- (1) Serber, Z.; Selenko, P.; Hänsel, R.; Reckel, S.; Löhr, F.; Ferrell, J. E.; Wagner, G.; Dötsch, V. *Nat Protoc* **2006**, *1*, 2701–2709.
- (2) Ferrage, F.; Zoonens, M.; Warschawski, D. E.; Popot, J.-L.; Bodenhausen, G. *J Am Chem Soc* **2003**, *125*, 2541–2545.
- (3) Didenko, T.; Boelens, R.; Rüdiger, S. G. D. *Protein Eng Des Sel* **2011**, *24*, 99–103.
- (4) Delaglio, F.; Grzesiek, S.; Vuister, G.; Zhu, G.; Pfeifer, J.; Bax, A. *J Biomol NMR* **1995**, *6*, 277–293.
- (5) Augustyniak, R.; Ferrage, F.; Paquin, R.; Lequin, O.; Bodenhausen, G. *J Biomol NMR* **2011**, *50*, 209–218.
- (6) Waudby, C. A.; Christodoulou, J. *J Magn Reson* **2011**, *211*, 67–73.



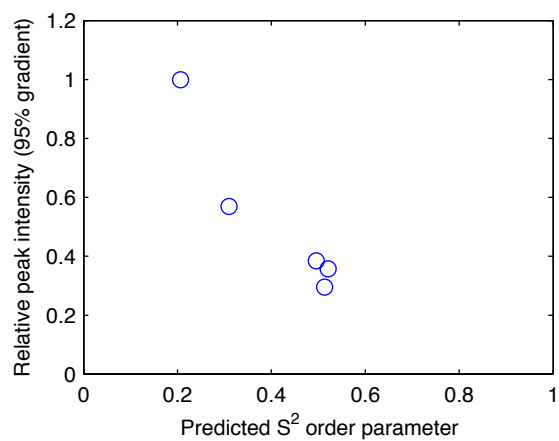
## Supplementary Figures



**Figure S1.**  $^1\text{H}$ - $^{15}\text{N}$  HSQC NMR spectra of *E. coli* cells in which ddFLN5 had been expressed (red), and purified ddFLN5 in bulk solution (blue).



**Figure S2.** Diffusion-edited (300 ms STE)  $^1\text{H}$ - $^{13}\text{C}$  HMQC NMR spectrum of [Ile- $^{13}\text{C}$ ] $_{\text{H}}$ -ddFLN5 expressed within *E. coli* cells (red), at the maximum accessible gradient strength ( $0.53 \text{ T m}^{-1}$ ), and the  $^1\text{H}$ - $^{13}\text{C}$  HMQC NMR spectrum of purified [Ile- $^{13}\text{C}$ ] $_{\text{H}}$ -ddFLN5 in bulk solution (grey).



**Figure S3.** Inverse correlation ( $r^2 = 0.90$ ) of intracellular ddFLN5 diffusion-edited HMQC peak intensities vs isoleucine methyl sidechain  $S^2$  order parameters predicted from the crystal structure (pdb 1QF8) (ref. 21).