



Universiteit
Leiden
The Netherlands

Probing spatial heterogeneity in supercooled glycerol and temporal heterogeneity with single-molecule FRET in polyprolines

Xia, T.

Citation

Xia, T. (2010, March 25). *Probing spatial heterogeneity in supercooled glycerol and temporal heterogeneity with single-molecule FRET in polyprolines*. Casimir PhD Series. Retrieved from <https://hdl.handle.net/1887/15122>

Version: Corrected Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/15122>

Note: To cite this publication please use the final published version (if applicable).

References

- [1] R. Zondervan, F. Kulzer, G. C. G. Berkhout and M. Orrit, “Local viscosity of supercooled glycerol near T_g probed by rotational diffusion of ensembles and single dye molecules”, *Proc. Natl. Acad. Sci. U. S. A.* **104** (2007) 12 628–12 633.
- [2] G. Adam and J. Gibbs, “On the temperature dependence of cooperative relaxation properties in glass-forming liquids”, *J. Chem. Phys.* **43** (1965) 139–146.
- [3] S. Glarum, “Dielectric relaxation of isoamyl bromide”, *J. Chem. Phys.* **33** (1960) 639–643.
- [4] H. Sillescu, “Heterogeneity at the glass transition: A review”, *Journal of Non-Crystalline Solids* **243** (1999) 81–108.
- [5] E. Donth, “The glass transition”, Springer-Verlag (2001).
- [6] R. Böhmer, R. V. Chamberlin, G. Diezemann, B. Geil, A. Heuer, S. C. Hinze, G. and Kuebler, R. Richert, H. Schiener, B. and Sillescu, H. W. Spiess, U. Tracht and M. Wilhelm, “Nature of the non-exponential primary relaxation in structural glass-formers probed by dynamically selective experiments”, *J. Non-Cryst. Solids* **235-237** (1998) 1–9.
- [7] G. Diezemann, R. Böhmer, G. Hinze and H. Sillescu, “Reorientational dynamics in simple supercooled liquids”, *J. Non-Cryst. Solids* **235** (1998) 121–127.
- [8] U. Tracht, M. Wilhelm, A. Heuer, H. Feng, K. Schmidt-Rohr and H. W. Spiess, “Length scale of dynamic heterogeneities at the glass transition determined by multidimensional nuclear magnetic resonance”, *Phys. Rev. Lett.* **81** (1998) 2727–2730.
- [9] B. Schiener, R. V. Chamberlin, G. Diezemann and R. Böhmer, “Non-resonant dielectric hole burning spectroscopy of supercooled liquids”, *J. Chem. Phys.* **107** (1997) 7746–7761.

-
- [10] U. Schneider, P. Lunkenheimer, R. Brand and A. Loidl, “Dielectric and far-infrared spectroscopy of glycerol”, *J. Non-Cryst. Solids* **235** (1998) 173–179.
- [11] A. Patkowski, T. Thurn-Albrecht, E. Banachowicz, W. Steffen, P. Bösecke, T. Narayanan and E. W. Fischer, “Long-range density fluctuations in orthoterphenyl as studied by means of ultrasmall-angle x-ray scattering”, *Phys. Rev. E: Stat. Phys., Plasmas, Fluids, Relat. Interdiscip. Top.* **61** (2000) 6909–6913.
- [12] A. Patkowski, E. W. Fischer, W. Steffen, H. Gläser, M. Baumann, T. Ruths and G. Meier, “Unusual features of long-range density fluctuations in glass-forming organic liquids: A Rayleigh and Rayleigh-Brillouin light scattering study”, *Phys. Rev. E: Stat. Phys., Plasmas, Fluids, Relat. Interdiscip. Top.* **63** (2001) 061 503.
- [13] M. T. Cicerone and M. D. Ediger, “Enhanced translation of probe molecules in supercooled o-terphenyl: Signature of spatially heterogeneous dynamics?”, *J. Chem. Phys.* **104** (1996) 7210–7218.
- [14] M. D. Ediger, “Spatially heterogeneous dynamics in supercooled liquids”, *Annu. Rev. Phys. Chem.* **51** (2000) 99–128.
- [15] L. A. Deschenes and D. A. Vanden Bout, “Heterogeneous dynamics and domains in supercooled o-terphenyl: A single molecule study”, *J. Phys. Chem. B* **106** (2002) 11 438–11 445.
- [16] A. Schob, F. Cichos, J. Schuster and C. von Borczyskowski, “Reorientation and translation of individual dye molecules in a polymer matrix”, *Eur. Polym. J.* **40** (2004) 1019–1026.
- [17] M. Orrit and J. Bernard, “Single pentacene molecules detected by fluorescence excitation in a p-terphenyl crystal”, *Phys. Rev. Lett.* **65** (1990) 2716–2719.
- [18] W. E. Moerner and L. Kador, “Optical detection and spectroscopy of single molecules in a solid”, *Phys. Rev. Lett.* **62** (1989) 2535–2538.
- [19] W. E. Moerner and M. Orrit, “Illuminating single molecules in condensed matter”, *Science* **283** (1999) 1670–1676.
- [20] F. Kulzer, T. Xia and M. Orrit, “Single molecules as optical nanoprobe for soft and complex matter”, *Angew. Chem., Int. Ed.* **49** (2010) 854–866.

-
- [21] D. Boyer, P. Tamarat, A. Maali, B. Lounis and M. Orrit, “Photothermal imaging of nanometer-sized metal particles among scatterers”, *Science* **297** (2002) 1160–1163.
- [22] S. Berciaud, D. Lasne, G. A. Blab, L. Cognet and B. Lounis, “Photothermal heterodyne imaging of individual metallic nanoparticles: theory versus experiment”, *Phys. Rev. B* **73** (2006) 045 424.
- [23] F. Kulzer, N. Laurens, J. Besser, T. Schmidt, M. Orrit and H. P. Spaink, “Photothermal detection of individual gold nanoparticles: Perspectives for high-throughput screening”, *ChemPhysChem* **9** (2008) 1761–1766.
- [24] P. M. R. Paulo, A. Gaiduk, F. Kulzer, S. F. G. Krens, T. Schmidt, M. Orrit and H. P. Spaink, “Photothermal correlation spectroscopy of gold nanoparticles in solution”, *J. Phys. Chem. C* **113** (2009) 11 451–11 457.
- [25] K. Lindfors, T. Kalkbrenner, P. Stoller and V. Sandoghdar, “Detection and spectroscopy of gold nanoparticles using supercontinuum white light confocal microscopy”, *Phys. Rev. Lett.* **93** (2004) 037 401.
- [26] H. Ewers, V. Jacobsen, E. Klotzsch, A. E. Smith, A. Helenius and V. Sandoghdar, “Label-free optical detection and tracking of single virions bound to their receptor in supported membrane bilayers”, *Nano Lett.* **7** (2007) 2263–2266.
- [27] P. Kukura, M. Celebrano, A. Renn and V. Sandoghdar, “Imaging a single quantum dot when it is dark”, *Nano Lett.* **9** (2009) 926–929.
- [28] F. G. Prendergast and K. Mann, “Chemical and physical properties of aequorin and the green fluorescent protein isolated from *Aequorea forskalea*”, *Biochemistry* **17** (1978) 3448–3453.
- [29] R. Tsien, “The green fluorescent protein”, *Annu. Rev. Biochem.* **67** (1998) 509–544.
- [30] H. P. Lu, L. Y. Xun and X. S. Xie, “Single-molecule enzymatic dynamics”, *Science* **282** (1998) 1877–1882.
- [31] G. Harms, G. Orr, M. Montal, B. Thrall, S. Colson and H. Lu, “Probing conformational changes of gramicidin ion channels by single-molecule patch-clamp fluorescence microscopy”, *Biophys. J.* **85** (2003) 1826–1838.

References

- [32] H. Lu, “Probing single-molecule protein conformational dynamics”, *Acc. Chem. Res.* **38** (2005) 557–565.
- [33] T. Förster, “Modern Quantum Chemistry”, Academic Press, New York (1965).
- [34] L. Stryer and R. Haugland, “Energy transfer: A spectroscopic ruler”, *Proc. Natl. Acad. Sci. U. S. A.* **58** (1967) 719–726.
- [35] T. Ha, T. Enderle, D. F. Ogletree, D. S. Chemla, P. R. Selvin and S. Weiss, “Probing the interaction between two single molecules: Fluorescence resonance energy transfer between a single donor and a single acceptor”, *Proc. Natl. Acad. Sci. U. S. A.* **93** (1996) 6264–6268.
- [36] J. Schütz, G. W. Trapesinger and T. Schmidt, “Direct observation of ligand colocalization on individual receptor molecules”, *Biophys. J.* **74** (1998) 2223–2226.
- [37] Y. Ishii, T. Yoshida, T. Funatsu, T. Wazawa and T. Yanagida, “Fluorescence resonance energy transfer between single fluorophores attached to a coiled-coil protein in aqueous solution”, *Chem. Phys.* **247** (1999) 163–173.
- [38] T. Ha, A. Y. Ting, J. Liang, W. B. Caldwell, A. A. Deniz, D. S. Chemla, P. G. Schultz and S. Weiss, “Biophysics single-molecule fluorescence spectroscopy of enzyme conformational dynamics and cleavage mechanism”, *Proc. Natl. Acad. Sci. USA* **96** (1999) 893–898.
- [39] S. Brasselet, E. J. G. Peterman, A. Miyawaki and W. E. Moerner, “Single-molecule fluorescence resonant energy transfer in calcium concentration dependent cameleon”, *J. Phys. Chem. B* **104** (2000) 3676–3682.
- [40] A. A. Deniz, T. A. Laurence, G. S. Beligere, M. Dahan, A. B. Martin, D. S. Chemla, P. E. Dawson, P. G. Schultz and S. Weiss, “Single-molecule protein folding: diffusion fluorescence resonance energy transfer studies of the denaturation of chymotrypsin inhibitor 2”, *Proc. Natl. Acad. Sci. U. S. A.* **97** (2000) 5179–5184.
- [41] X. W. Zhuang, L. E. Bartley, H. P. Babcock, R. Russell, T. J. Ha, D. Herschlag and S. Chu, “A single-molecule study of RNA catalysis and folding”, *Science* **288** (2000) 2048–2052.

-
- [42] B. Schuler, E. A. Lipman and W. A. Eaton, “Probing the free-energy surface for protein folding with single-molecule fluorescence spectroscopy (vol 419, pg 743, 2002)”, *Nature* **421** (2003) 94.
- [43] B. Schuler, E. A. Lipman, P. J. Steinbach, M. Kumke and W. A. Eaton, “Polyproline and the ‘spectroscopic ruler’ revisited with single-molecule fluorescence”, *Proc. Natl. Acad. Sci. U. S. A.* **102** (2005) 2754–2759.
- [44] W. Koopmans, R. Buning, T. Schmidt and J. van Noort, “spFRET using Alternating Excitation and FCS reveals progressive DNA unwrapping in nucleosomes”, *Biophys. J.* **10** (2009) 195–204.
- [45] T. Basché, S. Kummer and C. Bräuchle, “Direct spectroscopic observation of quantum jumps of a single molecule”, *Nature* **373** (1995) 132–134.
- [46] R. Zondervan, F. Kulzer, H. van der Meer, J. A. J. M. Disselhorst and M. Orrit, “Laser-driven microsecond temperature cycles analyzed by fluorescence polarization microscopy”, *Biophys. J.* **90** (2006) 2958–2969.
- [47] P. G. de Gennes, “A simple picture for structural glasses”, *C. R. Phys.* **3** (2002) 1263–1268.
- [48] E. R. Weeks and D. A. Weitz, “Properties of cage rearrangements observed near the colloidal glass transition”, *Phys. Rev. Lett.* **89** (2002) 095 704.
- [49] J. C. Conrad, P. P. Dhillon, E. R. Weeks, D. R. Reichman and D. A. Weitz, “Contribution of slow clusters to the bulk elasticity near the colloidal glass transition”, *Phys. Rev. Lett.* **97** (2006) 265 701.
- [50] M. M. Hurley and P. Harrowell, “Kinetic structure of a 2-dimensional liquid”, *Phys. Rev. E* **52** (1995) 1694–1698.
- [51] C. Bennemann, C. Donati, J. Baschnagel and S. C. Glotzer, “Growing range of correlated motion in a polymer melt on cooling towards the glass transition”, *Nature* **399** (1999) 246–249.
- [52] J. D. Stevenson, J. Schmalian and P. G. Wolynes, “The shapes of cooperatively rearranging regions in glass-forming liquids”, *Nat. Phys.* **2** (2006) 268–274.
- [53] L. Berthier, G. Biroli, J. P. Bouchaud, L. Cipelletti, D. El Masri, D. L’Hôte, F. Ladieu and M. Pierno, “Direct experimental evidence of

- a growing length scale accompanying the glass transition”, *Science* **310** (2005) 1797–1800.
- [54] R. F. Berg, M. R. Moldover and G. A. Zimmerli, “Viscoelasticity of Xenon near the critical point”, *Phys. Rev. Lett.* **82** (1999) 920–923.
- [55] P. Sollich, F. Lequeux, P. Hébraud and M. E. Cates, “Rheology of soft glassy materials”, *Phys. Rev. Lett.* **78** (1997) 2020–2023.
- [56] F. Varnik, L. Bocquet, J. L. Barrat and L. Berthier, “Shear localization in a model glass”, *Phys. Rev. Lett.* **90** (2003) 095 702.
- [57] K. Schröter and E. Donth, “Viscosity and shear response at the dynamic glass transition of glycerol”, *J. Chem. Phys.* **113** (2000) 9101–9108.
- [58] W. T. Laughlin and D. R. Uhlmann, “Viscous flow in simple organic liquids”, *J. Phys. Chem.* **76** (1972) 2317–2325.
- [59] F. J. Bermejo, A. Criado, A. de Andrés, E. Enciso and H. Schöber, “Microscopic dynamics of glycerol in its crystalline and glassy states”, *Phys. Rev. B* **53** (1996) 5259–5267.
- [60] D. Bonn, S. Tanase, B. Abou, H. Tanaka and J. Meunier, “Laponite: aging and shear rejuvenation of a colloidal glass”, *Phys. Rev. Lett.* **89** (2002) 015 701.
- [61] D. Bonn, H. Tanaka, P. Coussot and J. Meunier, “Ageing, shear rejuvenation and avalanches in soft glassy materials”, *J. Phys.-Condens. Matter* **16** (2004) S4987–4992.
- [62] H. A. Kramers, “Brownian motion in a field of force and the diffusion model of chemical reactions”, *Physica* **7** (1940) 284–304.
- [63] A. J. Liu and S. R. Nagel, “Nonlinear dynamics - jamming is not just cool any more”, *Nature* **396** (1998) 21–22.
- [64] A. Widmer-Cooper, P. Harrowell and H. Fynewever, “How reproducible are dynamic heterogeneities in a supercooled liquid?”, *Phys. Rev. Lett.* **93** (2004) 135 701.
- [65] G. Tarjus, S. A. Kivelson, Z. Nussinov and P. Viot, “The frustration-based approach of supercooled liquids and the glass transition: a review and critical assessment”, *J. Phys.-Condens. Matter* **17** (2005) R1143–1182.

-
- [66] G. Biroli and J. P. Bouchaud, “Critical fluctuations and breakdown of Stokes-Einstein relation in the mode-coupling theory of glasses”, arXiv:cond-mat/0609705v1 (2006).
- [67] J. P. Bouchaud, “Granular media: some ideas from statistical physics”, arXiv:cond-mat/0211196v2 (2002).
- [68] J. T. Bendler, J. J. Fontanella and M. F. Shlesinger, “The defect diffusion model and the properties of glasses and liquids”, *J. Non-Cryst. Solids* **352** (2006) 4835–4842.
- [69] A. Reiser and G. Kasper, “On the pressure dependence of fragility”, *Europhys. Lett.* **76** (2006) 1137–1143.
- [70] E. W. Fischer, “Light-scattering and dielectric studies on glass-forming liquids”, *Physica. A* **201** (1993) 183–206.
- [71] P. G. de Gennes, “A simple picture for structural glasses”, *C. R. Phys.* **3** (2002) 1263–1268.
- [72] K. Schröter and E. Donth, “Comparison of shear response with other properties at the dynamic glass transition of different glass formers”, *J. Non-Cryst. Solids* **307** (2002) 270–280.
- [73] D. R. Reichman and P. Charbonneau, “Mode-coupling theory”, *J. Stat. Mech.-Theory Exp.* **2005** (2005) P05 013.
- [74] R. Zondervan, T. Xia, H. van der Meer, C. Storm, F. Kulzer, W. van Saarloos and M. Orrit, “Soft glassy rheology of supercooled molecular liquids”, *Proc. Natl. Acad. Sci. U. S. A.* **105** (2008) 4993–4998 (Chapter 2 of this thesis).
- [75] K. Schröter, S. A. Hutcheson, X. Shi, A. Mandanici and G. B. McKenna, “Dynamic shear modulus of glycerol: Corrections due to instrument compliance”, *J. Chem. Phys.* **125** (2006) 214 507.
- [76] J. L. Cox (ed.), “Natural Gas Hydrates : Properties, Occurrence, and Recovery”, Butterworth (1983).
- [77] R. C. Weast (ed.), “Handbook of Chemistry and Physics”, The Chemical Rubber Co. (1968).
- [78] Y. H. Jeong, “Frequency-dependent shear modulus of glycerol near the glass-transition”, *Phys. Rev. A* **36** (1987) 766–773.

- [79] G. Tammann and E. Jenckel, “Die Kristallisationsgeschwindigkeit und die Kernzahl des Glycerins in Abhaengigkeit von der Temperatur”, *Z. Anorg. Allg. Chem.* **193** (1930) 76–80.
- [80] A. Ha, I. Cohen, X. L. Zhao, M. Lee and D. Kivelson, “Supercooled liquids and polyamorphism”, *J. Chem. Phys.* **100** (1996) 1–4.
- [81] I. Cohen, A. Ha, X. L. Zhao, M. Lee, T. Fischer, M. J. Strouse and D. Kivelson, “A low-temperature amorphous phase in a fragile glass-forming substance”, *J. Chem. Phys.* **100** (1996) 8518–8526.
- [82] H. Tanaka, R. Kurita and H. Mataka, “Liquid-liquid transition in the molecular liquid triphenyl phosphite”, *Phys. Rev. Lett.* **92** (2004) 025 701–025 704.
- [83] R. Kurita and H. Tanaka, “Critical-like phenomena associated with liquid-liquid transition in a molecular liquid”, *Science* **306** (2004) 845–848.
- [84] A. Hédoux, Y. Guinet, P. Derollez, O. Hernandez, R. Lefort and M. Descamps, “A contribution to the understanding of the polyamorphism situation in triphenyl phosphite”, *Phys. Chem. Chem. Phys.* **6** (2004) 3192–3199.
- [85] R. Kurita, Y. Shinohara, Y. Amemiya and H. Tanaka, “Microscopic structural evolution during the liquid-liquid transition in triphenyl phosphite”, *J. Phys.: Condens. Matter* **19** (2007) 152 101.
- [86] M. M. Hurley and P. Harrowell, “Kinetic structure of a 2-dimensional liquid”, *Phys. Rev. E: Stat. Phys., Plasmas, Fluids, Relat. Interdiscip. Top.* **52** (1995) 1694–1698.
- [87] R. S. Miller and R. A. MacPhail, “Ultraslow nonequilibrium dynamics in supercooled glycerol by stimulated Brillouin gain spectroscopy”, *J. Chem. Phys.* **106** (1997) 3393–3401.
- [88] R. S. Miller and R. A. MacPhail, “Physical aging in supercooled glycerol: evidence for heterogeneous dynamics?”, *J. Phys. Chem. B* **101** (1997) 8635–8641.
- [89] S. Reinsberg, X. H. Qiu, M. Wilhelm, H. W. Spiess and M. D. Ediger, “Length scale of dynamic heterogeneity in supercooled glycerol near T_g ”, *J. Chem. Phys.* **114** (2001) 7299–7302.

-
- [90] H. Jinnai, H. Yoshida, K. Kimishima, Y. Funaki, Y. Hirokawa, A. E. Ribbe and H. Hashimoto, “Observation of fine structures in bicontinuous phase-separated domains of a polymer blend by laser scanning confocal microscopy”, *Macromolecules* **34** (2001) 5186–5191.
- [91] H. Aoki, Y. Sakurai, S. Ito and T. Nakagawa, “Phase-separation structure of a monolayer of binary polymer blend studied by fluorescence scanning near-field optical microscopy”, *J. Phys. Chem. B* **103** (1999) 10 553–10 556.
- [92] Y. Hirokawa, H. Jinnai, Y. Nishikawa, T. Okamoto and T. Hashimoto, “Direct observation of internal structures in poly (N-isopropylacrylamide) chemical gels”, *Macromolecules* **32** (1999) 7093–7099.
- [93] C. A. Helm, H. Möhwald, K. Kjaer and J. Als-Nielsen, “Phospholipid monolayers between fluid and solid states”, *Biophys. J.* **52** (1987) 381–390.
- [94] T. Baumgart, S. T. Hess and W. W. Webb, “Imaging coexisting fluid domains in biomembrane models coupling curvature and line tension”, *Nature* **425** (2003) 821–824.
- [95] S. L. Veatch and S. Keller, “Separation of liquid phases in giant vesicles of ternary mixtures of phospholipids and cholesterol”, *Biophys. J.* **85** (2003) 3074–3083.
- [96] R. Zondervan, F. Kulzer, S. B. Orlinskii and M. Orrit, “Photoblinking of rhodamine 6G in poly(vinyl alcohol): radical dark state formed through the triplet”, *J. Phys. Chem. A* **107** (2003) 6770–6776.
- [97] R. Kurita, K. Murata and H. Tanaka, “Control of fluidity and miscibility of a binary liquid mixture by the liquid-liquid transition”, *Nat. Mater.* **7** (2008) 647–652.
- [98] A. Donald, “Food for thought”, *Nat. Mater.* **3** (2004) 579–581.
- [99] H. Tanaka, “General view of a liquid-liquid phase transition”, *Phys. Rev. E* **62** (2000) 6968–6976.
- [100] J. Carpenter, M. Agamalian, K. Littrell, P. Thiyagarajan and C. Rehm, “Time-of-flight implementation of an ultra-small-angle neutron scattering instrument”, *J. Appl. Crystallogr.* **36** (2003) 763–768.

References

- [101] T. Mason, M. Arai and K. Clausen, “Next-generation neutron sources”, *MRS Bull.* **28** (2003) 923–928.
- [102] Y. B. Melnichenko and G. D. Wignall, “Small-angle neutron scattering in materials science: Recent practical applications”, *Journal of Applied Physics* **102** (2007) 201 101.
- [103] A. Dupuis, G. Zaccai and M. Satre, “Neutron small-angle scattering studies of ribonuclease in mixed aqueous solutions and determination of the preferentially bound water”, *Biochemistry* **22** (1984) 5951–5956.
- [104] G. Zaccai, G. Bunick and H. Eisenberg, “Denaturation of a halophilic enzyme monitored by small-angle neutron scattering”, *J. Mol. Biol.* **192** (1986) 155–157.
- [105] A. VanHook, “Crystallization: Theory and Practice”, Reinhold Publishing Corporation (1961).
- [106] M. Massa, M. Lee and K. Danlnoki-Veress, “Crystal nucleation of polymers confined to droplets: Memory effects”, *J Polym Sci , Part B: Polym Phys* **43** (2005) 3438–3443.
- [107] B. E. Schwickert, S. R. Kline, H. Zimmermann, K. M. Lantzky and J. L. Yarger, “Early stages of glacial clustering in supercooled triphenyl phosphite”, *Phys. Rev. B* **64** (2001) 045 410.
- [108] S. B. Smith, L. Finzi and C. Bustamante, “Direct mechanical measurements of the elasticity of single DNA molecules by using magnetic beads”, *Science* **258** (1992) 1122–1126.
- [109] S. B. Smith, Y. Cui and C. Bustamante, “Overstretching B-DNA: the elastic response of individual double-stranded and single-stranded DNA molecules”, *Science* **271** (1996) 795–799.
- [110] M. D. Wang, H. Yin, R. Landick, J. Gelles and S. M. Block, “Stretching DNA with optical tweezers”, *Biophys. J.* **72** (1997) 1335–1346.
- [111] M. Rief, H. Clausen-Schaumann and H. Gaub, “Sequence dependent mechanics of single DNA molecules”, *Nat. Struct. Mol. Biol.* **6** (1999) 346–349.
- [112] M. Kellermayer, S. Smith, H. Granzier and C. Bustamante, “Folding-unfolding transition in single titin molecules characterized with laser tweezers”, *Science* **276** (1997) 1112–1116.

-
- [113] L. Tskhovrebova, J. Trinic, J. Sleep and R. Simmons, “Elasticity and unfolding of single molecules of the giant muscle protein titin”, *Nature* **378** (1997) 308–312.
- [114] A. Oberhauser, P. Marszalek, H. Erickson and J. Fernandez, “The molecular elasticity of the extracellular matrix protein tenascin”, *Nature* **393** (1998) 181–185.
- [115] B. Brower-Toland, C. Smith, R. Yeh, J. Lis, C. Peterson and M. Wang, “Mechanical disruption of individual nucleosomes reveals a reversible multistage release of DNA”, *Proc. Natl. Acad. Sci. U. S. A.* **99** (2002) 1960–1965.
- [116] B. Brower-Toland, D. A. Wacker, R. M. Fulbright, J. T. Lis, W. L. Kraus and M. D. Wang, “Specific contributions of histone tails and their acetylation to the mechanical stability of nucleosomes”, *J. Mol. Biol.* **346** (2005) 135–146.
- [117] M. Kruihof, F.-T. Chien, A. Routh, C. Logie, D. Rhodes and J. van Noort, “Single-molecule force spectroscopy reveals a highly compliant helical folding for the 30-nm chromatin fiber”, *Nat. Struct. Mol. Biol.* **16** (2009) 534–540.
- [118] F.-T. Chien and J. van Noort, “10 years of tension on chromatin: results from single-molecule force spectroscopy”, *Curr. Pharm. Biotechnol.* **10** (2009) 474–485.
- [119] A. Hards, C. Zhou, M. Seitz, C. Bräuchle and A. Zumbusch, “Simultaneous AFM manipulation and fluorescence imaging of single DNA strands”, *ChemPhysChem.* **6** (2005) 534–540.
- [120] S. Hohng, R. Zhou, M. K. Nahas, J. Yu, K. Schulten, D. M. J. Lilley and T. Ha, “Fluorescence-force spectroscopy maps two-dimensional reaction landscape of the Holliday junction”, *Science* **318** (2007) 279–283.
- [121] A. Gaiduk, R. Kühnemuth, S. Felekyan, M. Antonik, W. Becker, V. Kudryavtsev, C. Sandhagen and C. Seidel, “Fluorescence detection with high time resolution: From optical microscopy to simultaneous force and fluorescence spectroscopy”, *Microscopy Research and Technique* **70** (2007) 433–441.
- [122] J. van Mameren, M. Modesti, R. Kanaar, C. Wyman, E. Peterman and G. Wuite, “Counting rad51 proteins disassembling from nucleoprotein filaments under tension”, *Nature* **457** (2009) 745–748.

References

- [123] X. Michalet, A. Kapanidis, T. Laurence, F. Pinaud, S. Doose, M. Pflughoeft and S. Weiss, “The power and prospects of fluorescence microscopies and spectroscopies”, *Annu. Rev. Biophys. Biomol. Struct.* **32** (2003) 161–182.
- [124] M. Böhmer and J. Enderlein, “Fluorescence spectroscopy of single molecules under ambient conditions: Methodology and technology”, *Chem Phys Chem* **4** (2003) 792–808.
- [125] G. Haran, “Topical review: Single-molecule fluorescence spectroscopy of biomolecular folding”, *J. Phys.: Condens. Matter* **15** (2003) R1291–R1317.
- [126] S. de Keijzer, A. Sergé, F. van Hemert, P. Lommerse, G. Lamers, H. Spaink, T. Schmidt and B. Snaar-Jagalska, “A spatially restricted increase in receptor mobility is involved in directional sensing during *Dictyostelium discoideum* chemotaxis”, *J. Cell Sci.* **121** (2008) 1750–1757.
- [127] B. Schuler, E. A. Lipman and W. A. Eaton, “Probing the free-energy surface for protein folding with single-molecule fluorescence spectroscopy”, *Nature* **419** (2002) 743–747.
- [128] J. R. Lakowicz, “Principles of fluorescence spectroscopy (Third edition)”, Springer (2006).
- [129] E. Boukobza, A. Sonnenfeld and G. Haran, “Immobilization in surface-tethered lipid vesicles as a new tool for single-biomolecule spectroscopy”, *J. Phys. Chem. B* **105** (2001) 12 165–12 170.
- [130] C. Wu, R. Komoroski and L. Mandelkern, “The observation of *cis* residues in poly(l-proline) in aqueous solution.”, *Macromolecules* **8** (1975) 635–637.
- [131] S. Doose, H. Neuweiler, H. Barsch and M. Sauer, “Probing polyproline structure and dynamics by photoinduced electron transfer provides evidence for deviations from a regular polyproline type II helix”, *Proc. Natl. Acad. Sci. U. S. A.* **104** (2007) 17 400–17 405.
- [132] R. Best, K. Merchant, I. Gopich, B. Schuler, A. Bax and W. Eaton, “Effect of flexibility and *cis* residues in single-molecule FRET studies of polyproline”, *Proc. Natl. Acad. Sci. U. S. A.* **104** (2007) 18 964–18 969.

-
- [133] N. Helbecque and M. Loucheux-Lefebvre, “Critical chain length for polyproline-II structure formation in H-Gly-(Pro)_n-OH”, *Int. J. Pept. Protein. Res.* **19** (1982) 94–101.
- [134] J. Jacob, B. Baker, R. Bryant and D. Cafiso, “Distance estimates from paramagnetic enhancements of nuclear relaxation in linear and flexible model peptides”, *Biophys. J.* **77** (1999) 1086–1092.
- [135] C. Grathwohl and K. Wüthrich, “NMR studies of the rates of proline *cis*–*trans* isomerization in oligopeptides”, *Biopolymers* **20** (2004) 2623–2633.
- [136] L. P. Watkins, H. Y. Chang and H. Yang, “Quantitative single-molecule conformational distributions: A case study with poly-(L-proline)”, *J. Phys. Chem. A* **110** (2006) 5191–5203.
- [137] H. Sahoo, D. Roccatano, A. Hennig and W. Nau, “A 10-Å spectroscopic ruler applied to short polyprolines”, *J. Am. Chem. Soc.* **129** (2007) 9762–9772.
- [138] B. Valeur, “Molecular fluorescence: principles and applications”, Wiley–VCH (2002).
- [139] B. Müller, E. Zaychikov, C. Bräuchle and D. Lamb, “Pulsed interleaved excitation”, *Biophys. J.* **89** (2005) 3508–3522.
- [140] A. Kapanidis, N. Lee, T. Laurence, S. Doose, E. Margeat and S. Weiss, “Fluorescence-aided molecular sorting: Analysis of structure and interactions by alternating-laser excitation of single molecules”, *Proc. Natl. Acad. Sci. U. S. A.* **101** (2004) 8936–8941.
- [141] P. Bodis, R. Timmer, S. Yeremenko, W. J. Buma, J. S. Hannam, D. A. Leigh and S. Wouterson, “Heterovibrational interactions, cooperative hydrogen bonding, and vibrational energy relaxation pathways in a rotaxane”, *J. Phys. Chem. C* **111** (2007) 6798–6804.
- [142] P. Bodis, M. R. Panman, B. H. Bakker, M. Prato, W. J. Buma, A. M. Brouwer, E. R. Kay, D. A. Leigh and S. Wouterson, “Two-dimensional vibrational spectroscopy of rotaxane-based molecular machines”, *Acc. Chem. Res.* **42** (2009) 1462–1469.

References
