Assembling anisotropic colloidal building blocks

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Publication List

Work presented in this thesis

- Vera Meester and Daniela J. Kraft, *Spherical, dimpled and crumpled hybrid colloids with tunable surface morphology*, Langmuir, 32 (41), 10668-10677, **2016**.
(results from Chapter 2)
- Vera Meester, Ruben W. Verweij, Casper M. van der Wel and Daniela J. Kraft, *Colloidal recycling: Reconfiguration of random aggregates into patchy particles*, ACS nano, 10 (4), 4322-4329, **2016**.
(results from Chapter 3)
- Vera Meester and Daniela J. Kraft, *Complex patchy particles shaped from deformable seed particles by capillary interactions*, Soft Matter, 14, 1162-1170, **2018**.
(results from Chapter 4)
- Vera Meester and Daniela J. Kraft, *Patchy particles with two distinct patch types*, in preparation.
(results from Chapter 5)
- Vera Meester, Casper M. van der Wel, Ruben W. Verweij, Giovanni Biondaro and Daniela J. Kraft, *Anisotropic distortions in hexagonal crystals at fluid interfaces*, in preparation.
(results from Chapter 6)

Additional appreciation for work in this thesis

- Vera Meester, LION image award, Leiden University, published in Volkskrant in November **2016**.
(results from Chapter 2)
- Vera Meester, Best presentation award, Casimir Spring School, presentation title: *Colloidal recycling: Reconfiguration of random aggregates into patchy particles*, **2016**.
(results from Chapter 3)

Other publications

- Janne-Mieke Meijer, Vera Meester, Fabian Hagemans, Albert P. Philipse and Andrei Petukhov, *Convectively assembled crystals of colloidal cubes*, in preparation.
- Indrani Chakraborty, Vera Meester, Casper M. van der Wel and Daniela J. Kraft, *Colloidal joints with designed motion range and tunable joint flexibility*, Nanoscale, 9, 7814-7821, **2017**.
- Jan Hilhorst, Vera Meester, Esther Groeneveld, Jan K. G. Dhont and Henk N. W. Lekkerkerker, *Structure and Rheology of Mixed Suspensions of Montmorillonite and Silica Nano-particles*, Journal of Physical Chemistry B, 118 (40), 11816-11825, **2014**.
- Peter Holmqvist, Vera Meester, Fabian Westermeijer and Dzina Kleshchanok, *Rotational diffusion in concentrated platelet systems measured with X-ray photon correlation spectroscopy*, The Journal of Chemical Physics, 139, 084905, **2013**.
- Dzina Kleshchanok, Vera Meester, Cornelia E. Pompe, Jan Hilhorst and Henk N. W. Lekkerkerker, *Effects of added silica nanoparticles on hectorite gels*, Journal of Physical Chemistry B, 116 (31), 9532-9539, **2012**.

Curriculum Vitae

I was born in 1988 in Amersfoort and grew up in a small town nearby, Spakenburg. In 2008 I enrolled in the bachelor *Chemisty* at Utrecht University, where I specialized in physical chemistry with the minor *Nanosciences*. My bachelor graduation project was performed in collaboration with NIZO food research in Ede where we studied the effect of casein molecules on the texture of clay suspensions. During my studies I've also worked as a study coach for teenagers with study and social difficulties.
I graduated in 2011 (GPA 3.72) and subsequently started with the master *Nanomaterials: Chemistry and Physics* at Utrecht University. Two research projects were performed. One study was performed at Utrecht University at the department of Physical and Colloid Chemistry, where I synthesized hollow silica cubes and studied their self-assembly into large compact structures. The second project was performed at Oxford University where I formed networks of alternating strings of dia- and superparamagnetic particles under the influence of an external magnetic field. I finished my masters in 2014 (GPA 4.00). During my master I also worked as a researcher on a separate research project at Utrecht University involving the visco-elastic and dynamic properties of clay suspensions.
In March 2014 I started as a PhD-candidate in the newly established Soft Matter Physics group of Dr. Daniela Kraft at Leiden University. I developed a method to recycle colloidal aggregates by reconfiguration into patchy shapes and formed anisotropic colloids of various shapes. I also studied the effect of anisotropic particles on the hexagonal order of spheres at a fluid interface and the dynamics of these impurities under confinement. During my PhD I've supervised research projects of high school, bachelor, master and MBO students and presented my work at several national and international conferences. Besides research I've been motivated to promote and communicate science to a wider audience via interviews, labtours, competitions and presentations, which led to participation in Famelab and winning the LION Image Award and the Best Presentation Prize at the Casimir Spring School in 2016.
In June 2018 I'll start a new adventure as a Junior Scientist Innovator at the department of Explosions, Ballistics and Protection of TNO in Rijswijk.

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Bibliography

[1] P. C. Hiemenz and R. Rajagopalan, *Principles of Colloid and Surface Chemistry*, Third (Marcel Dekker Inc, New York, 1997).

[2] S. C. Glotzer and M. J. Solomon, "Anisotropy of building blocks and their assembly into complex structures", Nature Materials **6**, 557–562 (2007).

[3] S. Sacanna, M. Korpics, K. Rodriguez, L. Colón-Meléndez, S.-H. Kim, D. J. Pine, and G.-R. Yi, "Shaping colloids for self-assembly.", Nature Communications **4**, 1688 (2013).

[4] H. R. Sheu, M. S. El-Aasser, and J. W. Vanderhoff, "Phase separation in polystyrene latex interpenetrating polymer networks", Journal of Polymer Science, Part A: Polymer Chemistry **28**, 629–651 (1990).

[5] G.-R. Yi, V. N. Manoharan, E. Michel, M. T. Elsesser, S.-M. Yang, and D. J. Pine, "Colloidal Clusters of Silica or Polymer Microspheres", Advanced Materials **16**, 1204–1208 (2004).

[6] S. Sacanna, W. T. M. Irvine, and D. J. Pine, "Lock and key colloids through polymerization-induced buckling of monodisperse silicon oil droplets", Soft Matter **7**, 1631–1634 (2011).

[7] H. R. Sheu, M. S. El-Aasser, and J. W. Vanderhoff, "Uniform nonspherical latex particles as model interpenetrating polymer networks", Journal of Polymer Science Part A: Polymer Chemistry **28**, 653–667 (1990).

[8] R. Arshady, "Suspension, emulsion, and dispersion polymerization: A methodological survey", Colloid and Polymer Science **270**, 717–732 (1992).

[9] J. W. Kim, R. J. Larsen, and D. A. Weitz, "Uniform nonspherical colloidal particles with tunable shapes", Advanced Materials **19**, 2005–2009 (2007).

[10] B. G. P. Van Ravensteijn and W. K. Kegel, "Tuning particle geometry of chemically anisotropic dumbbell-shaped colloids", Journal of Colloid and Interface Science **490**, 462–477 (2017).

[11] S. Sacanna, W. T. M. Irvine, P. M. Chaikin, and D. J. Pine, "Lock and key colloids", Nature **464**, 575–578 (2010).

[12]S. Knoche and J. Kierfeld, "Buckling of spherical capsules", Physical Review E **84**, 046608 (2011).

[13]G. Meng, N. Arkus, M. P. Brenner, and V. N. Manoharan, "The Free-Energy Landscape of Clusters of Attractive Hard Spheres", Science **327**, 560–563 (2010).

[14]V. Manoharan, M. Elsesser, and P. D.J., "Dense packing and symmetry in small clusters of microspheres", Science **301**, 483–487 (2003).

[15]A. B. Pawar and I. Kretzschmar, "Patchy particles by glancing angle deposition", Langmuir **24**, 355–358 (2008).

[16]D. J. Kraft, W. S. Vlug, C. M. Van Kats, A. Van Blaaderen, A. Imhof, and W. K. Kegel, "Self-assembly of colloids with liquid protrusions", Journal of the American Chemical Society **131**, 1182–1186 (2009).

[17]J. Du and R. K. O'Reilly, "Anisotropic particles with patchy, multicompartment and Janus architectures: preparation and application", Chemical Society Reviews **40**, 2402–2416 (2011).

[18]A. B. Pawar and I. Kretzschmar, "Fabrication , Assembly , and Application of Patchy Particles", Macromolecular rapid communications **31**, 150–168 (2010).

[19]Z. Zhang and S. C. Glotzer, "Self-assembly of patchy particles", Nano Letters **4**, 1407–1413 (2004).

[20]Y. Wang, A. D. Hollingsworth, S. K. Yang, S. Patel, D. J. Pine, and M. Weck, "Patchy Particle Self-Assembly via Metal Coordination", Journal of the American Chemical Society **135**, 14064–14067 (2013).

[21]Q. Chen, S. C. Bae, and S. Granick, "Directed self-assembly of a colloidal kagome lattice", Nature **469**, 381–384 (2011).

[22]S. Jiang, Q. Chen, M. Tripathy, E. Luijten, K. S. Schweizer, and S. Granick, "Janus Particle Synthesis and Assembly", Advanced Materials **22**, 1060–1070 (2010).

[23]L. Hong, S. Jiang, and S. Granick, "Simple method to produce janus colloidal particles in large quantity", Langmuir **22**, 9495–9499 (2006).

[24]J. W. Kim, R. J. Larsen, and D. A. Weitz, "Synthesis of nonspherical colloidal particles with anisotropic properties", Journal of the American Chemical Society **128**, 14374–14377 (2006).

[25]Y. Wang, Y. Wang, D. R. Breed, V. N. Manoharan, L. Feng, A. D. Hollingsworth, M. Weck, and D. J. Pine, "Colloids with valence and specific directional bonding", Nature **491**, 51–55 (2012).

[26]J. Israelachvili, *Intramolecular and surface forces*, Third ed. (Academic Press, Santa Barbara, 2011), pp. 253–266.

[27] V. Meester, *Magnetic-field induced structure formation in mixtures of superparamagnetic and diamagnetic colloids in a ferrofluid*, tech. rep. (University of Oxford, Oxford, 2014).

[28] M. E. Leunissen, A. van Blaaderen, A. D. Hollingsworth, M. T. Sullivan, and P. M. Chaikin, "Electrostatics at the oil-water interface, stability, and order in emulsions and colloids.", Proceedings of the National Academy of Sciences **104**, 2585–2590 (2007).

[29] D. J. Kraft, R. Ni, F. Smallenburg, M. Hermes, K. Yoon, D. A. Weitz, and A. V. Blaaderen, "Surface roughness directed self-assembly of patchy particles into colloidal micelles", Proceedings of the National Academy of Sciences **109**, 10787–10792 (2012).

[30] P. Pieranski, "Two-dimensional interfacial colloidal crystals", Physical Review Letters **45**, 569–572 (1980).

[31] Y. Yang, Z. Fang, X. Chen, W. Zhang, Y. Xie, Y. Chen, Z. Liu, and W. Yuan, "An overview of pickering emulsions: Solid-particle materials, classification, morphology, and applications", Frontiers in Pharmacology **8**, 1–20 (2017).

[32] M. Kamp, M. Hermes, C. M. Van Kats, D. J. Kraft, W. K. Kegel, M. Dijkstra, and A. Van Blaaderen, "Selective Depletion Interactions in Mixtures of Rough and Smooth Silica Spheres", Langmuir **32**, 1233–1240 (2016).

[33] W. T. M. Irvine, M. J. Bowick, and P. M. Chaikin, "Fractionalization of interstitials in curved colloidal crystals", Nature Materials **11**, 948–951 (2012).

[34] V. W. A. de Villeneuve, R. Dullens, D. Aarts, E. Groeneveld, H. Scherff, W. Kegel, and H. Lekkerkerker, "Colloidal Hard-Sphere Crystal Growth Frustrated by Large Spherical Impurities", Science **309**, 1231–1233 (2005).

[35] P. Pieranski, "Colloidal crystals", Contemporary Physics **24**, 25–73 (1983).

[36] D. R. Nelson, *Defects and Geometry in Condensed Matter Physics*, First edit (Cambridge University Press, Cambridge, 2002).

[37] W. T. M. Irvine, V. Vitelli, and P. M. Chaikin, "Pleats in crystals on curved surfaces", Nature **468**, 947–951 (2010).

[38] S. J. Gerbode, S. H. Lee, C. M. Liddell, and I. Cohen, "Restricted dislocation motion in crystals of colloidal dimer particles", Physical Review Letters **101**, 1–4 (2008).

[39] S. J. Gerbode, D. C. Ong, C. M. Liddell, and I. Cohen, "Dislocations and vacancies in two-dimensional mixed crystals of spheres and dimers", Physical Review E **82**, 1–7 (2010).

[40] E. Vignati, R. Piazza, and T. P. Lockhart, "Pickering Emulsions : Interfacial Tension , Colloidal Layer Morphology , and Trapped-Particle Motion", Langmuir **19**, 6650–6656 (2003).

[41]Y. C. Jung and B. Bhushan, "Contact angle , adhesion and friction properties of micro- and nanopatterned polymers for superhydrophobicity", Nanotechnology **17**, 4970–4980 (2006).

[42]V. N. Manoharan, "Colloids at interfaces: Pinned down", Nature Materials **14**, 869–870 (2015).

[43]B. M. Guy, M. Hermes, and W. C. K. Poon, "Towards a Unified Description of the Rheology of Hard-Particle Suspensions", Physical Review Letters **115**, 088304 (2015).

[44]J. R. Royer, D. L. Blair, and S. D. Hudson, "Rheological Signature of Frictional Interactions in Shear Thickening Suspensions", Physical Review Letters **116**, 188301 (2016).

[45]N. Y. C. Lin, B. M. Guy, M. Hermes, C. Ness, J. Sun, W. C. K. Poon, and I. Cohen, "Hydrodynamic and Contact Contributions to Continuous Shear Thickening in Colloidal Suspensions", Physical Review Letters **115**, 228304 (2015).

[46]S. Badaire, C. Cottin-Bizonne, and A. D. Stroock, "Experimental investigation of selective colloidal interactions controlled by shape, surface roughness, and steric layers", Langmuir **24**, 11451–11463 (2008).

[47]J. R. Wolters, G. Avvisati, F. Hagemans, T. Vissers, D. J. Kraft, M. Dijkstra, and W. K. Kegel, "Self-assembly of "Mickey Mouse" shaped colloids into tube-like structures: experiments and simulations", Soft Matter **11**, 1067–1077 (2015).

[48]K. Zhao and T. G. Mason, "Directing colloidal self-assembly through roughness-controlled depletion attractions", Physical Review Letters **99**, 268301 (2007).

[49]C. I. Zoldesi and A. Imhof, "Synthesis of monodisperse colloidal spheres, capsules, and microballoons by emulsion templating", Advanced Materials **17**, 924–928 (2005).

[50]M. Okubo, H. Minami, and K. Morikawa, "Influence of shell strength on shape transformation of micron-sized , monodisperse , hollow polymer particles", Colloid and Polymer Science **281**, 214–219 (2003).

[51]G. A. Vliegenthart and G. Gompper, "Compression, crumpling and collapse of spherical shells and capsules", New Journal of Physics **13**, 045020 (2011).

[52]C. Quilliet, C. Zoldesi, C. Riera, A. V. Blaaderen, and A. Imhof, "Anisotropic colloids through non-trivial buckling", The European Physical Journal E **27**, 13–20 (2008).

[53]L. Zhang, J. Wu, Y. Wang, Y. Long, N. Zhao, and J. Xu, "Combination of Bioinspiration: A General Route to Superhydrophobic Particles", Journal of the American Chemical Society **134**, 9879–9881 (2012).

[54] A. Perro, S. Reculusa, E. Bourgeat-Lami, E. Duguet, and S. Ravaine, "Synthesis of hybrid colloidal particles: From snowman-like to raspberry-like morphologies", Colloids and Surfaces A: Physicochemical and Engineering Aspects **284**, 78–83 (2006).

[55] M. D'Acunzi, L. Mammen, M. Singh, X. Deng, M. Roth, G. K. Auernhammer, and H.-j. Butt, "Superhydrophobic surfaces by hybrid raspberry-like particles", Faraday Discussions **146**, 35–48 (2010).

[56] N. Puretskiy and L. Ionov, "Synthesis of Robust Raspberry-like Particles Using Polymer Brushes", Langmuir **27**, 3006–3011 (2011).

[57] T. Song, T. Liu, X. Yang, and F. Bai, "Raspberry-like particles via the heterocoagulated reaction between reactive epoxy and amino groups", Colloids and Surfaces A: Physicochemical and Engineering Aspects **469**, 60–65 (2015).

[58] B. Peng and A. Imhof, "Surface morphology control of cross-linked polymer particles via dispersion polymerization", Soft Matter **11**, 3589–3598 (2015).

[59] M. T. Elsesser, A. D. Hollingsworth, K. V. Edmond, and D. J. Pine, "Large Core - Shell Poly(methyl methacrylate) Colloidal Clusters : Synthesis , Characterization , and Tracking", Langmuir **27**, 917–927 (2011).

[60] B. Thomson, A. Rudin, and G. Lajoie, "Dispersion Copolymerization of Styrene and Divinylbenzene . II . Effect of Crosslinker on Particle Morphology", Journal of Applied Polymer Science **59**, 2009–2028 (1996).

[61] C. Graf, D. L. J. Vossen, A. Imhof, and A. V. Blaaderen, "A General Method To Coat Colloidal Particles with Silica", Langmuir **19**, 6693–6700 (2003).

[62] Y. Lu, J. Mclellan, and Y. Xia, "Synthesis and Crystallization of Hybrid Spherical Colloids Composed of Polystyrene Cores and Silica Shells", Langmuir **20**, 3464–3470 (2004).

[63] A. Perro and V. N. Manoharan, "Bulk Synthesis of Polymer - Inorganic Colloidal Clusters", Langmuir **26**, 18669–18675 (2010).

[64] Y. Lan, Y. Wu, A. Karas, and O. A. Scherman, "Photoresponsive Hybrid Raspberry-Like Colloids Based on Cucurbit[8]uril Host – Guest Interactions", Angewandte Chemie - International Edition **53**, 2166–2169 (2014).

[65] W. Ming, D. Wu, R. V. Benthem, and G. D. With, "Superhydrophobic Films from Raspberry-like Particles", Nano Letters **5**, 2298–2301 (2005).

[66] R.-k. Wang, H.-r. Liu, and F.-w. Wang, "Facile Preparation of Raspberry-Like Superhydrophobic Polystyrene Particles via Seeded Dispersion Polymerization", Langmuir **29**, 11440–11448 (2013).

[67] C. Sun, Z.-z. Gu, and H. Xu, "Packing the Silica Colloidal Crystal Beads: A Facile Route to Superhydrophobic Surfaces", Langmuir **25**, 12439–12443 (2009).

[68]C. M. Tseng, Y. Y. Lu, and J. W. Vanderhoff, "Uniform Polymer Particles by Dispersion Polymerization in Alcohol", Journal of Polymer Science Part A: Polymer Chemistry **24**, 2995–3007 (1986).

[69]L. R. Herndon and E. E. Reid, "the Decomposition of Organic Compounds At High Temperatures and Pressures", J. Am. Chem. Soc. **50**, 3066–3073 (1928).

[70]Y. Wei, G.-W. Jang, C.-C. Chan, K. F. Hsueh, R. Hariharan, S. A. Patel, and C. K. Whitecar, "Polymerization of Aniline and Alkyl ring-Substituted Anilines in the Presence of Aromatic Additives", Journal of Physical Chemistry **94**, 7716–7721 (1990).

[71]C. I. Zoldesi, I. L. Ivanovska, C. Quilliet, G. J. L. Wuite, and A. Imhof, "Elastic properties of hollow colloidal particles", Physical Review E **78**, 051401 (2008).

[72]S. S. Datta, S.-h. Kim, J. Paulose, A. Abbaspourrad, D. R. Nelson, and D. A. Weitz, "Delayed Buckling and Guided Folding of Inhomogeneous Capsules", Physical Review Letters **109**, 134302 (2012).

[73]M. Okubo, R. Takekoh, and A. Suzuki, "Preparation of micron-sized , monodisperse poly (methyl methacrylate)/polystyrene composite particles having a large number of dents on their surfaces by seeded dispersion polymerization in the presence of decalin", Journal of Polymer Science **280**, 1057–1061 (2002).

[74]C. van der Wel, K. B. Rohit, R. W. Verweij, H. C. Frijters, Z. Gong, A. D. Hollingsworth, S. Sacanna, and D. J. Kraft, "Preparation of colloidal organosilica spheres through spontaneous emulsification", Langmuir **33**, 8174–8180 (2017).

[75]W. M. Haynes, D. Lide, and T. Bruno, *Handbook of Chemistry and Physics*, 94 (2013), pp. 15046–15047.

[76]S. I. R. Castillo, S. Ouhajji, S. Fokker, B. H. Erné, C. T. W. M. Schneijdenberg, D. M. E. Thies-Weesie, and A. P. Philipse, "Silica cubes with tunable coating thickness and porosity: From hematite filled silica boxes to hollow silica bubbles", Microporous and Mesoporous Materials **195**, 75–86 (2014).

[77]J. D. Halverson and A. V. Tkachenko, "DNA-programmed mesoscopic architecture", Physical Review E **87**, 062310 (2013).

[78]Z. Zeravcic, V. N. Manoharan, and M. P. Brenner, "Size limits of self-assembled colloidal structures made using specific interactions", Proceedings of the National Academy of Sciences **111**, 15918–15923 (2014).

[79]F. Romano and F. Sciortino, "Colloidal self-assembly: patchy from the bottom up", Nature Materials **10**, 171–173 (2011).

[80]P. F. Damasceno, M. Engel, and S. C. Glotzer, "Predictive Self-Assembly of Polyhedra into Complex Structures", Science **337**, 453–458 (2012).

[81] E. Bianchi, R. Blaak, and C. N. Likos, "Patchy colloids: state of the art and perspectives", Physical Chemistry Chemical Physics **13**, 6397–6410 (2011).

[82] A. Reinhardt and D. Frenkel, "Numerical Evidence for Nucleated Self-Assembly of DNA Brick Structures", Physical Review Letters **112**, 238103 (2014).

[83] A. Murugan, Z. Zeravcic, M. P. Brenner, and S. Leibler, "Multifarious assembly mixtures : Systems allowing retrieval of diverse stored structures", Proceedings of the National Academy of Sciences **112**, 54–59 (2014).

[84] K. L. Young, M. L. Personick, M. Engel, P. F. Damasceno, S. N. Barnaby, R. Bleher, T. Li, S. C. Glotzer, B. Lee, and C. a. Mirkin, "A directional entropic force approach to assemble anisotropic nanoparticles into superlattices", Angewandte Chemie **52**, 13980–13984 (2013).

[85] J. A. Millan, D. Ortiz, G. Van Anders, and S. C. Glotzer, "Self-assembly of archimedean tilings with enthalpically and entropically patchy polygons", ACS Nano **8**, 2918–2928 (2014).

[86] G. Van Anders, D. Klotsa, N. K. Ahmed, M. Engel, and S. C. Glotzer, "Understanding shape entropy through local dense packing", Proceedings of the National Academy of Sciences **111**, E4812–E4821 (2014).

[87] B. Ruzicka, E. Zaccarelli, L. Zulian, R. Angelini, M. Sztucki, A. Moussaïd, T. Narayanan, and F. Sciortino, "Observation of empty liquids and equilibrium gels in a colloidal clay", Nature Materials **10**, 56–60 (2011).

[88] F. Smallenburg and F. Sciortino, "Liquids more stable than crystals in particles with limited valence and flexible bonds", Nature Physics **9**, 554–558 (2013).

[89] L. Hong, A. Cacciuto, E. Luijten, and S. Granick, "Clusters of Charged Janus Spheres", Nano Letters **6**, 2510–2514 (2006).

[90] Q. Chen, E. Diesel, J. K. Whitmer, S. C. Bae, E. Luijten, and S. Granick, "Triblock Colloids for Directed Self-Assembly", Journal of the American Chemical Society **133**, 7725–7727 (2011).

[91] K. Chaudhary, Q. Chen, J. J. Jua, S. Granick, and J. A. Lewis, "Janus Colloidal Matchsticks", Journal of the American Chemical Society **134**, 12901–12903 (2012).

[92] J. Yan, M. Bloom, S. C. Bae, E. Luijten, and S. Granick, "Linking synchronization to self-assembly using magnetic Janus colloids", Nature **491**, 578–581 (2012).

[93] J. Yan, K. Chaudhary, S. C. Bae, J. A. Lewis, and S. Granick, "Colloidal ribbons and rings from Janus magnetic rods", Nature Communications **4**, 1516–1519 (2013).

[94]A. A. Shah, M. Ganesan, J. Jocz, and M. J. Solomon, "Direct Current Electric Field Assembly of Colloidal Crystals Displaying Reversible Structural Color", ACS nano **8**, 8095–8103 (2014).

[95]A. Ruditskiy, B. Ren, and I. Kretzschmar, "Behaviour of iron oxide (Fe3O4) Janus particles in overlapping external AC electric and static magnetic fields", Soft Matter **9**, 9174–9181 (2013).

[96]S. Sacanna, L. Rossi, and D. J. Pine, "Magnetic click colloidal assembly", Journal of the American Chemical Society **134**, 6112–6115 (2012).

[97]A. A. Shah, B. Schultz, W. Zhang, S. C. Glotzer, and M. J. Solomon, "Actuation of shape-memory colloidal fibres of Janus ellipsoids.", Nature Materials **14**, 117–124 (2014).

[98]Q. Chen, S. C. Bae, and S. Granick, "Directed self-assembly of a colloidal kagome lattice", Nature **469**, 381–384 (2011).

[99]Q. Chen, S. C. Bae, and S. Granick, "Staged self-assembly of colloidal metastructures", Journal of the American Chemical Society **134**, 11080–11083 (2012).

[100]S. Sacanna and D. J. Pine, "Shape-anisotropic colloids: Building blocks for complex assemblies", Current Opinion in Colloid and Interface Science **16**, 96–105 (2011).

[101]K. J. Lee, J. Yoon, and J. Lahann, "Recent advances with anisotropic particles", Current Opinion in Colloid and Interface Science **16**, 195–202 (2011).

[102]M. Grzelczak, J. Vermant, E. M. Furst, and L. M. Liz-Marzán, "Directed self-assembly of nanoparticles", ACS Nano **4**, 3591–3605 (2010).

[103]D. D. L. Heras, J. M. Tavares, and M. M. T. Da Gama, "Phase diagrams of binary mixtures of patchy colloids with distinct numbers and types of patches: The empty fluid regime", Journal of Chemical Physics **134**, 5615–5626 (2011).

[104]J. Appel, S. Akerboom, R. G. Fokkink, and J. Sprakel, "Facile one-step synthesis of monodisperse micron-sized latex particles with highly carboxylated surfaces.", Macromolecular rapid communications **34**, 1284–8 (2013).

[105]A. M. Yake, R. A. Panella, C. E. Snyder, and D. Velegol, "Fabrication of colloidal doublets by a salting out-quenching-fusing technique", Langmuir **22**, 9135–9141 (2006).

[106]C. van der Wel, N. Bossert, Q. J. Mank, M. G. T. Winter, D. Heinrich, and D. J. Kraft, "Surfactant-free Colloidal Particles with Specific Binding Affinity", Langmuir **33**, 9803–9810 (2017).

[107]D. A. Weitz, J. S. Huang, and Sung, "Dynamics of Diffusion-Limited Kintetic Aggregation", Physical Review Letters **53**, 1657–1660 (1984).

[108] P. J. Flory and J. Rehner, "Statistical Mechanics of Cross-Linked Polymer Networks", The Journal of Adhesion **11**, 521–526 (1943).

[109] A. B. Pawar, M. Caggioni, R. W. Hartel, and P. T. Spicer, "Arrested coalescence of viscoelastic droplets with internal microstructure", Faraday Discussions **158**, 341–350 (2012).

[110] E. B. Mock, H. De Bruyn, B. S. Hawkett, R. G. Gilbert, and C. F. Zukoski, "Synthesis of anisotropic nanoparticles by seeded emulsion polymerization", Langmuir **22**, 4037–4043 (2006).

[111] J. Russo, J. M. Tavares, P. I. C. Teixeira, M. M. T. Da Gama, and F. Sciortino, "Re-entrant phase behaviour of network fluids: A patchy particle model with temperature-dependent valence", Journal of Chemical Physics **135**, 034501 (2011).

[112] W. K. Kegel, D. Breed, M. Elsesser, and D. J. Pine, "Formation of Anisotropic Polymer Colloids by Disparate Relaxation Times", Langmuir **22**, 7135–7136 (2006).

[113] D. J. Kraft, J. Groenewold, and W. K. Kegel, "Colloidal molecules with well-controlled bond angles", Soft Matter **5**, 3823–3826 (2009).

[114] M. Y. Lin, H. M. Lindsay, D. A. Weitz, R. C. Ball, R. Klein, and P. Meakin, "Universality in colloid aggregation", Nature **339**, 360–362 (1989).

[115] M. Smoluchowski, "Drei vortrage uber diffusion, Brownsche bewegung und koagulation von kolloidteilchen", Zeitschrift fur Physik **17**, 557–585 (1916).

[116] M. Smoluchowski, "Versuch einer mathematischen Theorie der Koagulationskinetic kolloider Losungen", Zeitschrift fur Physik **92**, 129–168 (1917).

[117] E. Koos, "Current Opinion in Colloid & Interface Science Capillary suspensions : Particle networks formed through the capillary force", Current Opinion in Colloid & Interface Science **19**, 575–584 (2014).

[118] B. G. P. Van Ravensteijn, M. Kamp, A. Van Blaaderen, and W. K. Kegel, "General route toward chemically anisotropic colloids", Chemistry of Materials **25**, 4348–4353 (2013).

[119] C. Van Der Wel, A. Vahid, A. Šarić, T. Idema, D. Heinrich, and D. J. Kraft, "Lipid membrane-mediated attraction between curvature inducing objects", Scientific Reports **6**, 1–10 (2016).

[120] S. S. Velankar, "A non-equilibrium state diagram for liquid/fluid/particle mixtures", Soft Matter **11**, 8393–8403 (2015).

[121] G.-R. Yi, D. J. Pine, and S. Sacanna, "Recent progress on patchy colloids and their self-assembly.", Journal of physics. Condensed matter **25**, 193101 (2013).

[122]F. Li, D. P. Josephson, and A. Stein, "Colloidal assembly: The road from particles to colloidal molecules and crystals", Angewandte Chemie **50**, 360–388 (2011).

[123]S. Sacanna, D. J. Pine, and G.-R. Yi, "Engineering shape: the novel geometries of colloidal self-assembly", Soft Matter **9**, 8096–8106 (2013).

[124]Q. Chen, J. K. Whitmer, S. Jiang, S. C. Bae, E. Luijten, and S. Granick, "Supracolloidal reaction kinetics of Janus spheres", Science **331**, 199–202 (2011).

[125]E. Bianchi, C. N. Likos, and G. Kahl, "Self-Assembly of Heterogeneously Charged Particles under Confinement", ACS Nano **7**, 4657–4667 (2013).

[126]Z. Zhang, A. S. Keys, T. Chen, and S. C. Glotzer, "Self-Assembly of Patchy Particles into Diamond Structures through Molecular Mimicry", Langmuir **21**, 11547–11551 (2005).

[127]E. G. Noya, C. Vega, J. P. Doye, and A. A. Louis, "The stability of a crystal with diamond structure for patchy particles with tetrahedral symmetry.", The Journal of Chemical Physics **132**, 234511 (2010).

[128]X. Mao, Q. Chen, and S. Granick, "Entropy favours open colloidal lattices", Nature Materials **12**, 217–222 (2013).

[129]F. Sciortino, E. Bianchi, J. F. Douglas, and P. Tartaglia, "Self-assembly of patchy particles into polymer chains : A parameter-free comparison between Wertheim theory and Monte Carlo simulation", The Journal of Chemical Physics **126**, 194903 (2007).

[130]L. Lu, X. Li, P. G. Vekilov, and G. E. Karniadakis, "Probing the Twisted Structure of Sickle Hemoglobin Fibers via Particle Simulations", Biophysics journal **110**, 2085–2093 (2016).

[131]J. J. McManus, P. Charbonneau, E. Zaccarelli, and N. Asherie, "The physics of protein self-assembly", Current Opinion in Colloid and Interface Science **22**, 73–79 (2016).

[132]F. Romano, E. Sanz, and F. Sciortino, "Role of the Range in the Fluid-Crystal Coexistence for a Patchy Particle Model", The Journal of Physical Chemistry B **113**, 15133–15136 (2009).

[133]S. H. Kim, G. R. Yi, K. H. Kim, and S. M. Yang, "Photocurable pickering emulsion for colloidal particles with structural complexity", Langmuir **24**, 2365–2371 (2008).

[134]Y.-S. Cho, G.-R. Yi, J.-M. Lim, S.-H. Kim, V. N. Manoharan, D. J. Pine, and S.-M. Yang, "Self-Organization of Bidisperse Colloids in Water Droplets", Journal of the American Chemical Society **127**, 15968–15975 (2005).

[135] A. Desert, C. Hubert, Z. Fu, L. Moulet, J. Majimel, P. Barboteau, A. Thill, M. Lansalot, E. Bourgeat-lami, E. Duguet, and S. Ravaine, "Synthesis and Site-Specific Functionalization of Tetravalent , Hexavalent , and Dodecavalent Silica Particles", Angewandte Chemie **52**, 11068–11072 (2013).

[136] X. Zheng, Y. Wang, Y. Wang, D. J. Pine, and M. Weck, "Thermal Regulation of Colloidal Materials Architecture through Orthogonal Functionalizable Patchy Particles", Chemistry of Materials **28**, 3984–3989 (2016).

[137] B. Bharti, D. Rutkowski, K. Han, A. U. Kumar, C. K. Hall, and O. D. Velev, "Capillary Bridging as a Tool for Assembling Discrete Clusters of Patchy Particles", Journal of the American Chemical Society **138**, 14948–14953 (2016).

[138] V. Meester, R. W. Verweij, C. Van Der Wel, and D. J. Kraft, "Colloidal Recycling: Reconfiguration of Random Aggregates into Patchy Particles", ACS Nano **10**, 4322–4329 (2016).

[139] N. Arkus, V. N. Manoharan, and M. P. Brenner, "Minimal energy clusters of hard spheres with short range attractions", Physical Review Letters **103**, 118303 (2009).

[140] M. Hoare and P. Pal, "Physical cluster mechanics: Statics and energy surfaces for monatomic systems", Advances in Physics **20**, 161–196 (1971).

[141] S. Mossa, F. Sciortino, P. Tartaglia, and E. Zaccarelli, "Ground-State Clusters for Short-Range Attractive and Long-Range Repulsive Potentials", Langmuir **20**, 10756–10763 (2004).

[142] E. Koos and N. Willenbacher, "Particle configurations and gelation in capillary suspensions", Soft Matter **8**, 3988–3994 (2012).

[143] E. Lauga and M. P. Brenner, "Evaporation-driven assembly of colloidal particles", Physical Review Letters **93**, 238301 (2004).

[144] Y. Min, M. Akbulut, K. Kristiansen, Y. Golan, and J. Israelachvili, "The role of interparticle and external forces in nanoparticle assembly", Nature Materials **7**, 527–538 (2008).

[145] Y. G. Durant and D. C. Sundberg, "Effects of Cross-Linking on the Morphology of Structured Latex Particles. 1. Theoretical Considerations", Macromolecules **29**, 8466–8472 (1996).

[146] C. S. Wagner, Y. Lu, and A. Wittemann, "Preparation of Submicrometer-Sized Clusters from Polymer Spheres Using Ultrasonication", Langmuir **24**, 12126–12128 (2008).

[147] D. J. Kraft, W. S. Vlug, C. M. Van Kats, A. Van Blaaderen, A. Imhof, and W. K. Kegel, "Self-Assembly of Colloids with Liquid Protrusions", Journal of the American Chemical Society **131**, 1182–1186 (2008).

[148]D. J. Kraft, J. Hilhorst, M. A. P. Heinen, M. J. Hoogenraad, B. Luigjes, and W. K. Kegel, "Patchy Polymer Colloids with Tunable Anisotropy Dimensions", The Journal of Physical Chemistry B **115**, 7175–7181 (2011).

[149]H. Mehrabian, J. Harting, and J. H. Snoeijer, "Soft particles at a fluid interface", Soft Matter **12**, 1062–1073 (2016).

[150]C. S. Wagner, B. Fischer, M. May, and A. Wittemann, "Templated assembly of polymer particles into mesoscopic clusters with well-defined configurations", Colloid and Polymer Science **288**, 487–498 (2010).

[151]P. A. Kralchevskyt and K. Nagayama, "Capillary Forces between Colloidal Particles", Langmuir **10**, 23–36 (1994).

[152]D. Stamou, C. Duschl, and D. Johannsmann, "Long-range attraction between colloidal spheres at the air-water interface: The consequence of an irregular meniscus", Physical Review E **62**, 5263 (2000).

[153]Z. Gong, T. Hueckel, G. R. Yi, and S. Sacanna, "Patchy particles made by colloidal fusion", Nature **550**, 234–238 (2017).

[154]V. Meester and D. J. Kraft, "Complex Patchy Colloids shaped from Deformable Seed Particles through Capillary Interactions", Soft Matter **14**, 1162–1170 (2018).

[155]S. Ni, J. Leemann, I. Buttinoni, L. Isa, and H. Wolf, "Programmable colloidal molecules from sequential capillarity-assisted particle assembly", Science advances **2**, 1–7 (2016).

[156]Y. S. Cho, G. R. Yi, S. H. Kim, M. T. Elsesser, D. R. Breed, and S. M. Yang, "Homogeneous and heterogeneous binary colloidal clusters formed by evaporation-induced self-assembly inside droplets", Journal of Colloid and Interface Science **318**, 124–133 (2008).

[157]E. Bianchi, G. Doppelbauer, L. Filion, M. Dijkstra, and G. Kahl, "Predicting patchy particle crystals: Variable box shape simulations and evolutionary algorithms", Journal of Chemical Physics **136** (2012) 10.1063/1.4722477.

[158]W. Bollman, *Crystal Defects and Crystalline Interfaces*, first (Springer-Verlag, Berlin, 1970).

[159]T. Wood, J. Lintuviori, A. Schofield, B. Marenduzzo, and W. Poon, "A Self-Quenched Defect Glass in a Colloid-Nematic Liquid Crystal Composite", Science **334**, 79–83 (2011).

[160]U. Gasser, "Crystallization in three- and two-dimensional colloidal suspensions", Journal of Physics: Condensed Matter **21**, 203101 (2009).

[161]P. V. Braun, S. A. Rinne, and F. García-Santamaría, "Introducing defects in 3D photonic crystals: State of the art", Advanced Materials **18**, 2665–2678 (2006).

[162]C. López, "Materials Aspects of Photonic Crystals", Advanced Materials **15**, 1679–1704 (2003).

[163] A. M. Alsayed, M. F. Islam, J. Zhang, P. J. Collings, and A. G. Yodh, "Premelting at Defects Within Bulk Colloidal Crystals", Science **309**, 1207–1210 (2005).

[164] W. Lechner, E. Scholl-Paschinger, and C. Dellago, "Displacement fields of point defects in two- dimensional colloidal crystals", Journal of Physics: Condensed Matter **20**, 1–7 (2008).

[165] G. Meng, J. Paulose, D. R. Nelson, and V. N. Manoharan, "Elastic Instability of a Crystal Growing on a Curved Surface", Science **343**, 634–637 (2014).

[166] D. J. Wales, "Chemistry, geometry, and defects in two dimensions", ACS Nano **8**, 1081–1085 (2014).

[167] D. Ershov, J. Sprakel, J. Appel, M. A. Cohen Stuart, and J. van der Gucht, "Capillarity-induced ordering of spherical colloids on an interface with anisotropic curvature", Proceedings of the National Academy of Sciences **110**, 9220–9224 (2013).

[168] H. Kusumaatmaja and D. J. Wales, "Defect motifs for constant mean curvature surfaces", Physical Review Letters **110**, 1–5 (2013).

[169] F. A. Lavergne, S. Diana, D. G. A. L. Aarts, and R. P. A. Dullens, "Equilibrium Grain Boundary Segregation and Clustering of Impurities in Colloidal Polycrystalline Monolayers", Langmuir **32**, 12716–12724 (2016).

[170] J. A. G. Briggs, J. D. Riches, B. Glass, V. Bartonova, G. Zanetti, and H.-G. Krausslich, "Structure and assembly of immature HIV", Proceedings of the National Academy of Sciences **106**, 11090–11095 (2009).

[171] R. P. Dullens, M. Claesson, D. Derks, A. Van Blaaderen, and W. K. Kegel, "Monodisperse core-shell poly (methyl methacrylate) latex colloids", Langmuir **19**, 5963–5966 (2003).

[172] M. T. Elsesser and A. D. Hollingsworth, "Revisiting the Synthesis of a Well-Known Comb-Graft Copolymer Stabilizer and Its Application to the Dispersion Polymerization of Poly(methyl methacrylate) in Organic Media", Langmuir **26**, 17989–17996 (2010).

[173] M. T. Elsesser, A. D. Hollingsworth, K. V. Edmond, and D. J. Pine, "Large Core-Shell Poly(methyl methacrylate) Colloidal Clusters: Synthesis, Characterization, and Tracking", Langmuir **27**, 917–927 (2011).

[174] R. Aveyard, B. P. Binks, J. H. Clint, P. D. Fletcher, T. S. Horozov, B. Neumann, V. N. Paunov, J. Annesley, S. W. Botchway, D. Nees, A. W. Parker, A. D. Ward, and A. N. Burgess, "Measurement of long-range repulsive forces between charged particles at an oil-water interface", Physical Review Letters **88**, 2461021 (2002).

[175]D. N. ten Napel, P. Liu, and A. P. Philipse, "Synthesis, Characterization and Interfacial Self-Assembly of Spherical Magnetic Colloids", Master (Utrecht University, 2016).

[176]J. Crocker and D. Grier, "Methods of Digital Video Microscopy for Colloidal Studies", Journal of Colloid and Interface Science **179**, 298–310 (1996).

[177]D. Allan, T. Caswell, N. Keim, and C. van der Wel, *Trackpy*, 2017.

[178]C. van der Wel and D. J. Kraft, "Automated tracking of colloidal clusters with sub-pixel accuracy and precision", Journal of Physics: Condensed Matter **29**, 044001 (2016).

[179]C. P. Kelleher, A. Wang, G. I. Guerrero-García, A. D. Hollingsworth, R. E. Guerra, B. J. Krishnatreya, D. G. Grier, V. N. Manoharan, and P. M. Chaikin, "Charged hydrophobic colloids at an oil-aqueous phase interface", Physical Review E - Statistical, Nonlinear, and Soft Matter Physics **92**, 062306 (2015).

[180]M. Oettel and S. Dietrich, "Colloidal Interactions at Fluid Interfaces", Langmuir **24**, 1425–1441 (2008).

[181]C. P. Kelleher, R. E. Guerra, A. D. Hollingsworth, and P. M. Chaikin, "Phase behavior of charged colloids at a fluid interface", Physical Review E **95**, 022602 (2017).

[182]F. Ghezzi and J. C. Earnshaw, "Formation of meso-structures in colloidal monolayers", Journal of Physics: Condensed Matter **9**, L517–L523 (1997).

[183]J. C. Fernández-Toledano, A. Moncho-Jordá, F. Martínez-López, and R. Hidalgo-Álvarez, "Spontaneous formation of mesostructures in colloidal monolayers trapped at the air-water interface: A simple explanation", Langmuir **20**, 6977–6980 (2004).

[184]M. N. van der Linden, D. El Masri, M. Dijkstra, and A. van Blaaderen, "Expansion of charged colloids after centrifugation: formation and crystallisation of long-range repulsive glasses", Soft Matter **9**, 11618 (2013).

[185]J. C. Everts, M. N. van der Linden, A. van Blaaderen, and R. van Roij, "Alternating strings and clusters in suspensions of charged colloids", Soft Matter **12**, 6610–6620 (2016).

[186]K. D. Danov, P. A. Kralchevsky, B. N. Naydenov, and G. Brenn, "Interactions between particles with an undulated contact line at a fluid interface: Capillary multipoles of arbitrary order", Journal of Colloid and Interface Science **287**, 121–134 (2005).

[187]V. S. J. Craig, "Very small bubbles at surfaces—the nanobubble puzzle", Soft Matter **7**, 40–48 (2011).

[188]H. Peng, G. R. Birkett, and A. V. Nguyen, "Progress on the Surface Nanobubble Story: What is in the bubble? Why does it exist?", Advances in Colloid and Interface Science **222**, 573–580 (2015).

[189]H. An, G. Liu, and V. S. J. Craig, "Wetting of nanophases: Nanobubbles, nanodroplets and micropancakes on hydrophobic surfaces", Advances in Colloid and Interface Science **222**, 9–17 (2015).

[190]F. A. Lavergne, "Dynamics of grain boundaries in two-dimensional colloidal crystals", PhD (University of Oxford, 2016).