

# Reactive Poly(*N*-vinylactams) as Versatile Building Blocks for the Design of Functional Modular Microgels

Andrij Pich

*DWI – Leibniz Institute for Interactive Materials  
Institute of Technical and Macromolecular Chemistry, RWTH Aachen University*

[pich@dwil.rwth-aachen.de](mailto:pich@dwil.rwth-aachen.de)

This presentation will focus on the modular design of functional microgels using pre-polymer approach. Reactive water-soluble stimuli-responsive copolymers were synthesized by RAFT copolymerization of cyclic *N*-vinylamides (*N*-vinylcaprolactam, *N*-vinylpiperidone and *N*-vinylpyrrolidone) with different functional monomers (methacrylic acid *N*-hydroxysuccinimide ester, pyridyldisulfide ethylmethacrylate, vinylamide, etc) [1-3]. The influence of different reaction parameters such as solvent type, temperature and CTA:initiator ratio were studied to optimize the polymerization conditions in order to obtain amphiphilic biocompatible copolymers with variable chemical composition, controlled molecular weight and narrow polydispersity (PDI).

Reactive copolymers can be used as tailored building blocks for the design of microgels by crosslinking in O/W emulsions. The integration of succinimide and pyridyldisulfide groups in copolymer structure allows fast conjugation to lysine or cysteine residues of proteins in water at mild conditions [4,5]. This allows encapsulation of enzymes in macromolecular cages during microgel formation process and regulation of their activity and storage stability. Conjugation of drugs to reactive copolymers followed by crosslinking to microgels is versatile approach to design of versatile drug containers for intracellular degradation and release of the payload [6]. Reactive water-soluble stimuli-responsive copolymers are versatile building blocks for the fabrication of biocompatible macromolecular materials like microgels, capsules, fibers or thin films with tunable chemical structure, crosslink density and reactive groups.

[1] H. Peng, M. Kather, K. Rübsam, F. Jakob, U. Schwaneberg, A. Pich, Water-Soluble Reactive Copolymers Based on Cyclic *N*-Vinylamides with Succinimide Side Groups for Bioconjugation with Proteins, *Macromolecules*, 2015, 48, 4256-4268.

[2] H. Peng, W. Xu, A. Pich, Temperature and pH Dual-Responsive Poly(vinylactam) Copolymers Functionalized with Amine Side Groups via RAFT Polymerization, *Polymer Chemistry* 2016, 7, 5011-5022.

[3] H. Peng, K. Rübsam, X. Huang, F. Jakob, M. Karperien, U. Schwaneberg, A. Pich, Reactive Copolymers Based on *N*-Vinylactams with Pyridyldisulfide Side Groups via RAFT Polymerization and Post-Modification via Thiol–Disulfide Exchange Reaction, *Macromolecules* 2016, 49, 7141–7154.

[4] H. Peng, K. Rübsam, F. Jakob, U. Schwaneberg, A. Pich, Tunable Enzymatic Activity and Enhanced Stability of Cellulase Immobilized in Biohybrid Nanogels, *Biomacromolecules* 2016, 17(11), 3619-3631.

[5] H. Peng, K. Rübsam, F. Jakob, P. Pazdzior, U. Schwaneberg, A. Pich, Reversible Deactivation of Enzymes by Redox-Responsive Nanogel Carriers, *Macromol. Rapid Commun.* 2016, 37, 1765–1771.

[6] H. Peng, X. Huang, L. Weger, A. Götz, M. Karperien, A. Pich, A Facile Approach to Thermo and Reduction Dual-Responsive Prodrug Nanogels for Intracellular Doxorubicin Delivery, *J. Mater. Chem.* 2016, 4, 7572-7583.

# Small-angle Neutron Scattering

**Andrea Scotti**

*Institute of Physical Chemistry, RWTH Aachen*

[scotti@pc.rwth-aachen.de](mailto:scotti@pc.rwth-aachen.de)

The fundamentals of a scattering experiment will be introduced. Then, the properties and the limits of neutron scattering will be highlighted and compared with other scattering techniques as light and X-ray scattering. Finally, the use of small-angle neutron scattering with contrast variation will be introduced; particular attention will be given to the newest examples of how this technique has been used to unravel and explore unique properties of microgels in the last decades.

# Fluorescence Imaging of Microgels

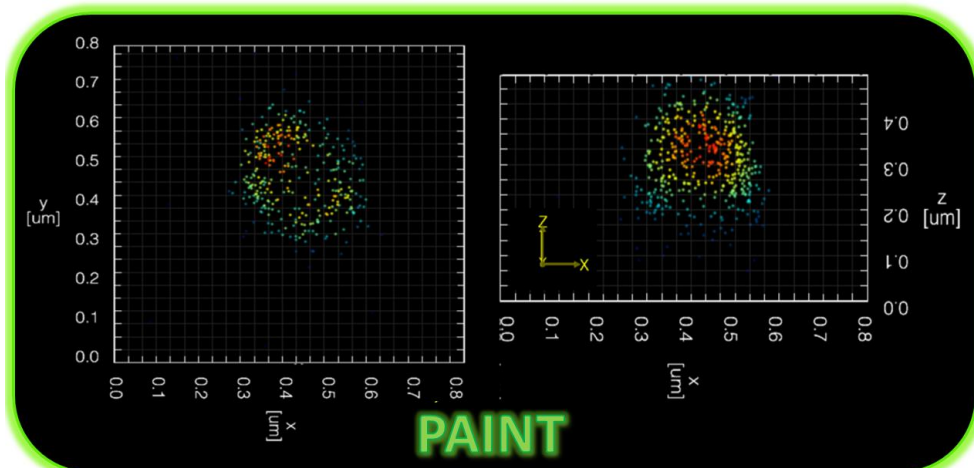
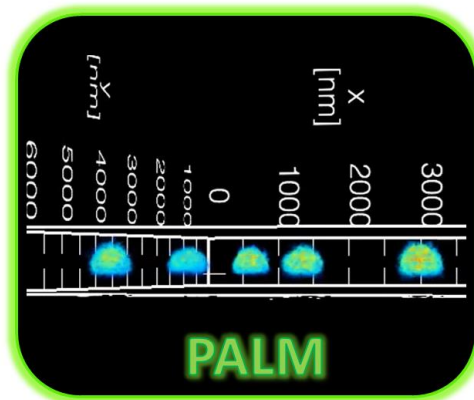
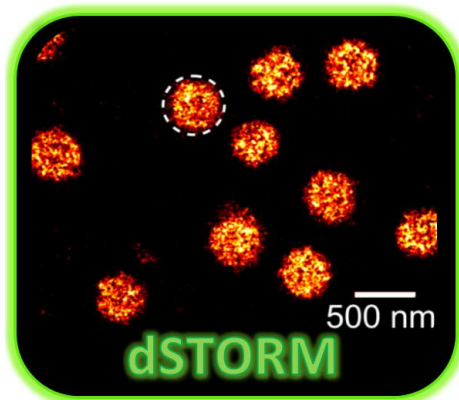
Dominik Wöll

*Institute of Physical Chemistry, RWTH Aachen University*

[woell@pc.rwth-aachen.de](mailto:woell@pc.rwth-aachen.de)

The elucidation of the structure of nano-compartmentalized soft matter systems, such as microgels, is challenging since they do not possess strong contrast for electron microscopy, and since classical fluorescence microscopy fails due to the fact that their structures are significantly smaller than the diffraction limit of optical light. However, modern superresolved fluorescence microscopy methods reach resolutions down to a few tens of nanometer and, therefore, are highly suited to fill this gap of structural *in situ* imaging. Many concepts and dye classes can be readily transferred from the experience of biological or medical superresolution imaging, yet several new challenges appeared.

In my talk, various types of superresolution fluorescence microscopy methods will be described and their advantages and challenges for imaging will be discussed. The concept behind (sometimes fancy) names such as dSTORM (direct stochastic optical reconstruction microscopy), PALM (photoactivated localization microscopy), PAINT (point accumulation for imaging in nanoscale topography), SOFI (super-resolution optical fluctuation imaging) and RESOLFT (reversible saturable optical linear fluorescence transitions) microscopy will be outlined.



# Using Microgels as Colloidal Building Blocks to Construct Functional Materials

**Brian Saunders**

*School of Materials, University of Manchester*

[brian.saunders@manchester.ac.uk](mailto:brian.saunders@manchester.ac.uk)

Microgels have for many years been viewed as model colloid particles for fundamental studies. However, in recent years their potential to be used for applications has become more actively studied. Indeed, many of the properties that microgels possess suit their use as building blocks to construct more complex (and versatile) materials or to enhance the properties of other materials within composites. In this both of these cases will be discussed. Firstly, the properties of microgels which favour application as building blocks will be reviewed. Then their use to construct injectable gels for load support will be examined. The ability to tune these interlinked microgel gels to give highly stretchable gels will also be considered. Finally, the ability to use microgels as an additive to enhance the performance of third generation solar cells will be discussed. In each case the fundamental principles that enable the successful application example will be discussed.

# Microgels for Building Blocks for Tissue Regenerative Materials

Laura De Laporte

*DWI – Leibniz Institute for Interactive Materials*

[delaporte@dwil.rwth-aachen.de](mailto:delaporte@dwil.rwth-aachen.de)

In modern medicine, the failure of organs or tissues due to accidents and diseases remains a major health problem with millions of affected patients each year and estimated costs of hundreds of billions US Dollars per year. Based on this issue, a new field of science emerged thirty years ago, called tissue engineering, in which scientists are combining engineering, biology, chemistry, and physics, to use different tools, methods, and molecules in order to form new tissues for functional restoration of impaired organs and replacement of lost parts. Tissue engineering can be divided into three subfields: i) material scaffolds with cells and growth factors to grow new tissues *ex vivo* in bioreactors for later implantation, ii) biohybrid materials with or without cells to trigger regeneration *in vivo*, and iii) *ex vivo* tissue models to study tissue formation and pathological processes in combination with drugs.

Over the last decades, several techniques have been developed to create tissue constructs in different sizes and complexities using two major concepts: implantable scaffolds or injectable hydrogels. Here, natural or synthetic materials are used, showing crucial differences in their properties. While natural materials, such as collagen, fibrin, and Matrigel® inherently contain many biological signals, artificial synthetic extra cellular matrices (ECM) are prepared with defined building blocks. To form functional tissue, these matrices aim to mimic the mechanical, biochemical, and structural properties of the ECM, including its degradability. When cells are incorporated during preparation, biocompatible chemistry under physiological conditions is required. Nowadays, most materials are biohybrid systems to combine controllability via synthetic materials with biological activity via natural compounds in a simplified way. In general, to produce artificial ECM constructs, dynamic material properties have to be designed at different scale-levels, from the physical, chemical, and biochemical properties of the molecules to the nano- and micrometer scale for structural elements and porosity, until the macroscopic architecture.

Modular design of hybrid polymeric biomaterials has the ability to mimic the natural ECM in a reductionist manner for different applications in biomedicine. Therefore, new material concepts and fabrication methods are required to synthesize building blocks in a bottom-up approach, which are assembled into defined and controlled functional 3D water-based structures. In addition, top-down technologies can be applied to create anisotropic hierarchical materials to mimic the complex architectures of various tissues. As building blocks, microgels and fibers are produced by technologies, such as fiber spinning, microfluidics, and in-mold polymerization. To arrange the building blocks in a spatially controlled manner, one can rely on self-assembly mechanisms and assembly by external fields (e.g., magnetic), or apply methods, such as photo-patterning and bioprinting. A better understanding of cellular processes in contact with synthetic biomaterials will supply information about the parameters, which are most important to make viable and functional regenerative materials for clinical use in a modular manner. By designing highly innovative but simple and elegant concepts based on synthetic polymeric materials and a versatile toolbox that can be engineered and adapted for multiple tissues, one can overcome current challenges in tissue engineering and enable clinical translation.

# Biomedical Applications of Synthetic Microgels

Andrés J. García

*Woodruff School of Mechanical Engineering, Petit Institute for Bioengineering and Bioscience, Georgia Institute of Technology*

[andres.garcia@me.gatech.edu](mailto:andres.garcia@me.gatech.edu)

Hydrogels, highly hydrated cross-linked polymer networks, have emerged as powerful synthetic analogs of extracellular matrices for basic cell studies as well as promising biomaterials for regenerative medicine applications. A critical advantage of these synthetic matrices over natural networks is that the biophysical and biochemical properties of the material can be tuned with high control and precision. Using microfluidics polymerization, we have engineered synthetic microgel platform with applications to various biomedical problems. Sample applications related to protein delivery, cell encapsulation, and delivery of immunomodulatory proteins will be discussed.

1: Foster GA, Headen DM, González-García C, Salmerón-Sánchez M, Shirwan H, García AJ. Protease-degradable microgels for protein delivery for vascularization. *Biomaterials*. 2017 Jan;113:170-175. doi: 10.1016/j.biomaterials.2016.10.044.

2: Liu AL, García AJ. Methods for Generating Hydrogel Particles for Protein Delivery. *Ann Biomed Eng*. 2016 Jun;44(6):1946-58. doi: 10.1007/s10439-016-1637-z.

3: Headen DM, Aubry G, Lu H, García AJ. Microfluidic-based generation of size-controlled, biofunctionalized synthetic polymer microgels for cell encapsulation. *Adv Mater*. 2014 May 21;26(19):3003-8. doi: 10.1002/adma.201304880.

4: Headen DM, Woodward KB, Coronel MM, Shrestha P, Weaver JD, Zhao H, et al. Local immunomodulation with Fas ligand-engineered biomaterials achieves allogeneic islet graft acceptance. *Nature Materials* 2018. doi: 10.1038/s41563-018-0099-0.

# Swelling, Structure and Thermodynamics of Ionic Microgels: Theoretical and Simulation Modeling

**Alan Denton**

*Physics, North Dakota State University*

[alan.denton@ndsu.edu](mailto:alan.denton@ndsu.edu)

Ionic microgels are soft colloidal particles composed of cross-linked polymer networks that swell and can acquire charge when dispersed in a solvent. The equilibrium size of an ionic microgel depends on a delicate balance of elastic and electrostatic osmotic pressures, which can be tuned by varying internal particle properties and external environmental conditions, such as temperature, pH, ionic strength, and concentration. The compressibility of these soft particles results in unusual bulk equilibrium and dynamical behavior compared with hard-sphere colloidal suspensions. Because of their tunable properties and ability to encapsulate cargo (e.g., drug or dye molecules), microgels have many practical applications, e.g., for drug delivery, biosensing, filtration, tissue engineering, and carbon capture.

Considering the many degrees of freedom of ionic microgels, large-scale molecular modeling can be computationally challenging. A practical approach to studying bulk phenomena is provided by coarse-grained models. Starting from an underlying microscopic model with many explicit particles, a coarse-grained model is derived by integrating out some degrees of freedom. In this lecture, I will discuss the background behind recent efforts to describe suspensions of ionic microgels within comprehensive coarse-grained models that combine the polymeric and colloidal natures of the particles. The models synthesize the internal free energy of polymer gels with effective elastic and electrostatic interactions between permeable, compressible, charged spheres. After outlining practical implementations of coarse-grained models via Monte Carlo and molecular dynamics simulations and Poisson-Boltzmann and thermodynamic perturbation theories, I will discuss illustrative results for equilibrium thermodynamic and structural properties at concentrations ranging from dilute to beyond particle overlap. Predictions from simulation and theory for swelling ratios, volume fractions, counterion distributions, and structural properties (radial distribution functions and static structure factors) reflect the particles' compressibility. Comparisons with experimental data for deionized, aqueous suspensions of PNIPAM particles demonstrate the capacity of coarse-grained models to predict and interpret measured swelling/deswelling behavior.

# Computer Simulations of Microgels in Solutions and at Interfaces

Igor Potemkin

*Physics Department, Lomonosov Moscow State University*

*DWI – Leibniz-Institute for Interactive Materials*

[igor@polly.phys.msu.ru](mailto:igor@polly.phys.msu.ru)

In the present paper, we report about new effects characteristic for the microgels, which (at the first glance) can be classified as counterintuitive. In particular, we demonstrate (i) inhomogeneous swelling of structurally homogeneous polyelectrolyte microgels revealing quasi-hollow central part and dense periphery [1], (ii) ability of polyampholyte core-shell microgels to serve as Coulomb trap, when charged shell of the microgel can serve as a potential barrier enforcing similarly charged nanoparticles (proteins) to “levitate” inside the core prohibiting their escape [2]. (iii) Microgels adsorbed at water-oil interface reveal peculiar behavior comprising ability either to homogeneously mix two immiscible liquids (oil and water) inside the microgel or to weakly segregate them [3,4]. Furthermore, the presence of amphiphilic (hydrophobic (A) and hydrophilic (B)) groups in the network facilitates mixing of the liquids. Random distribution of A and B groups leads to homogeneous mixing of the liquids. Blocky structure (each subchain comprises a diblock copolymer) is responsible for microphase segregation within the adsorbed microgel with corresponding segregation of the liquids: oil and water are preferably localized in hydrophobic and hydrophilic domains, respectively. (iv) Adsorption of microgels on porous surface leads to their peculiar behavior. We demonstrate that microgel collapse on the free surface leads to its penetration into the pore. On the other hand, swelling of the microgel within the pore is responsible for reversible exit of the microgel from the pore [5]. Both states (within and outside the pore) are thermodynamically stable. Internal structure of the microgel in the pore is studied. (v) We perform computer simulations of microgels with sliding cross-links. We demonstrate their adaptive structure revealing enhanced softness, deformability and permeability for guest-objects [6].

## Acknowledgements

The financial support of the Deutsche Forschungsgemeinschaft (DFG) within Collaborative Research Center SFB 985 “Functional Microgels and Microgel Systems”, the Russian Foundation for Basic Research is gratefully acknowledged.

## References

- [1] A.M. Romyantsev, A.A. Rudov, I.I. Potemkin, J. Chem. Phys. 2015, 142, 171105.
- [2] R. Schroeder, A. A. Rudov, W. Xu, I. V. Portnov, W. Richtering, I. I. Potemkin, A. Pich. Biomacromolecules, submitted.
- [3] R. A. Gumerov, A. M. Romyantsev, A. A. Rudov, A. Pich, W. Richtering, M. Moeller, I. I. Potemkin, ACS Macro Letters 2016, 5, 612-616.
- [4] A. M. Romyantsev, R. A. Gumerov, I. I. Potemkin, Soft Matter 2016, 12, 6799—6811.
- [5] I.V. Portnov, I.I. Potemkin, Macromolecules, submitted.
- [6] A.A. Gavrilov, I.I. Potemkin, Soft Matter 2018, accepted.



# Mesoscale Modeling of Polymer Microgels

**Alexander Alexeev**

*George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology*

[alexander.alexeev@me.gatech.edu](mailto:alexander.alexeev@me.gatech.edu)

Stimuli-sensitive microgels are an emerging class of soft materials that has been effectively employed in a variety of microscale applications such as sensing, actuation, drug delivery. In response to external stimuli, these micrometer-sized materials undergo a rapid and fully reversible volume transition, characterized by large volume changes and complex transformations in internal structure. We employ dissipative particle dynamics, a mesoscale particle-based computational method, to develop a computational model of stimuli-sensitive microgel particles in a viscous solvent. We use our computational approach to probe the microgel kinetics and to examine how the micromechanical properties of the microgels change as they go through the volume phase transition. We compare our results with Flory's and Tanaka's theories to characterize the swelling behavior of the gels. We then employ our mesoscale computational model to design microscopic devices actuated by stimuli-sensitive hydrogels.

# In Silico Synthesis of Microgels: Swelling, Elasticity and Effective Interactions

**Emanuela Zaccarelli**

*Institute for Complex Systems and Department of Physics, Sapienza University of Rome*

[emanuela.zaccarelli@phys.uniroma1.it](mailto:emanuela.zaccarelli@phys.uniroma1.it)

Microgels are soft particles individually made by cross-linked polymer networks which are nowadays widely used as a colloidal model system because of their swelling properties and their responsivity to external control parameters such temperature or pH. In the most used synthetic protocol, microgels have an inhomogeneous density profile characterized by a core-corona structure. The internal architecture thus affects the effective interactions between microgels at high densities. In addition, also temperature variations leading to a more compact structure will change the effective interactions. Thus, the simple Hertzian model for elastic spheres is only applicable to the fluid regime.

In order to go beyond this simplified picture, we have recently synthesized microgels in-silico using different preparation protocols able to provide a realistic description of the particles. To this aim, I will compare single-particle properties for varying crosslinker concentration and temperature with available experimental data, in particular the swelling behavior, the form factors and associated polymer density profiles, also in the light of the widely used fuzzy sphere model.

Next, I will focus on the single-particle mechanics by calculating all the elastic moduli of the individual particles in the small-deformation regime, again as a function of crosslinker concentration and temperature.

Finally, I will discuss recent effective interactions between two of such microgels, which we have calculated by the use of Umbrella Sampling Monte Carlo simulations and a generalised Widom insertion method. We find that that the Hertzian theory works well at large separations, and that in this regime the single-particle elastic moduli can indeed successfully predict the repulsive strength of the effective potential  $V(r)$ . However, for smaller separations, the two microgels are found to strongly interact and to become increasingly anisotropic. In this regime,  $V(r)$  significantly deviates from the predicted Hertzian behaviour in favor of a much stronger repulsion.

With this work we aim to establish a clear link between the microscopic network properties and the resulting microgel-microgel interactions, paving the way for a deeper understanding of the bulk behaviour of microgel suspensions.

# Characterizing and Engineering Internal Morphologies in Thermoresponsive Microgels

Todd Hoare

*Canada Research Chair in Engineered Smart Materials & Associate Professor*

*Department of Chemical Engineering, McMaster University*

[hoaretr@mcmaster.ca](mailto:hoaretr@mcmaster.ca)

The nature of a phase transition within a microgel is strongly dependent on not only its overall chemical composition but also its local chemical composition. In particular, using the conventional precipitation-based approach to fabricate thermoresponsive microgels, both radial (i.e. centre-out) and chain (i.e. the distribution of comonomers along a single polymer chain) can significantly influence both the phase transition behaviour as well as many other functional properties of a microgel. In this presentation, I will outline from both a theoretical and experimental perspective how we can both predict and control the distribution of crosslinks and/or functional comonomers within thermoresponsive microgels. In particular, the critical role of copolymerization kinetics in controlling both the radial and chain distributions of functional microgels will be emphasized, using a combination of a multi-component terminal copolymerization kinetics model that predicts local radial compositions<sup>1</sup> coupled with an osmotic pressure-based thermodynamics model that considers localized swelling within those local compositional regions<sup>2</sup>. The use of a variety of techniques including dynamic light scattering, zeta potential measurements, transmission electron microscopy, potentiometric titration, UV spectroscopy, and small angle neutron scattering, both alone and in concert<sup>3</sup>, will be discussed in terms of their practical utility to gain insight into microgel morphology. The key roles of microgel functional group distributions in controlling the multi-responsive swelling responses of microgels<sup>4</sup> as well as the performance of microgels as drug scavenging/delivery agents<sup>5-6</sup> will be highlighted as case studies of the importance of understanding functional group distributions. Finally, I will discuss more recent work done in my lab to actively change monomer and/or crosslinker distributions within microgels by altering temporal polymerization kinetics by using semi-batch monomer feeds<sup>7</sup> and/or changing the mechanism of microgel assembly by using pre-polymerized functionalized oligomers instead of monomers as the assembly unit<sup>8-9</sup>. This latter approach, a thermally-driven self-assembly process that mimics the mechanism of conventional microgel synthesis but results in more structurally homogeneous and degradable microgels, will be highlighted in terms of its capacity to offer significantly improved drug loadings and biologically compatible properties for potential translation to the clinic.

1. Hoare, T.; McLean, D., *J Phys Chem B* 2006, 110 (41), 20327-20336.
2. Hoare, T.; Pelton, R., *J Phys Chem B* 2007, 111 (41), 11895-11906.
3. Hoare, T.; Pelton, R., *J Colloid Interface Sci* 2006, 303 (1), 109-16.
4. Hoare, T.; Pelton, R., *Macromolecules* 2004, 37 (7), 2544-2550.
5. Hoare, T.; Pelton, R., *Langmuir* 2008, 24 (3), 1005-1012.
6. Hoare, T.; Young, S.; Lawlor, M. W.; Kohane, D. S., *Acta Biomater* 2012, 8 (10), 3596-3605.
7. Sheikholeslami, P.; Ewaschuk, C. M.; Ahmed, S. U.; Greenlay, B. A.; Hoare, T., *Colloid Polym Sci* 2012, 290 (12), 1181-1192.
8. Sivakumaran, D.; Mueller, E.; Hoare, T., *Langmuir* 2015, 31, 5767-5778.
9. Mueller, E.; Alsop, R. J.; Scotti, A.; Bleuel, M.; Rheinstädter, M. C.; Richtering, W.; Hoare, T., *Langmuir* 2018, 34 (4), 1601-1612.

# Microstructure, Transport Properties and Filtration Modeling of Microgel Suspensions

**Gerhard Nägele**

*Institute of Complex Systems, ICS-3, Forschungszentrum Jülich GmbH*

[g.naegele@fz-juelich.de](mailto:g.naegele@fz-juelich.de)

Microgel suspensions have interesting dynamical behavior reflected in suspension-averaged transport properties. These properties are determined by the interplay of direct (i.e., elastic and electro-steric) and solvent-mediated hydrodynamic interactions. In this presentation, theoretical methods are described for the calculation of dispersion-averaged transport properties including collective and self-diffusion coefficients, and the suspension viscosity. Results are presented both for non-ionic and ionic microgel systems. For weakly cross-linked ionic microgels, we account for their concentration-dependent de-swelling by the Denton-Tang method used to compute the equilibrium microgel size. Microstructural, thermodynamic and dynamic properties are discussed in particular regarding their dependence on the added salt and microgel concentration, and the microgel charge.

The predicted transport properties are the salient ingredient to the modeling of convective-diffusive particle transport in the crossflow filtration of microgel dispersions. In this industrially used process, a feed dispersion is steadily pumped through an array of hollow cylindrical membranes. A parameter-free model of cross-flow ultrafiltration is presented, and evaluated analytically by a boundary layer analysis, and numerically using a finite element method implemented in COMSOL. The concentration-polarization layer buildup of particles near a membrane, and the permeate flux through the membrane fiber are explored for different operating conditions. Filtration through a cylindrical membrane with alternating permeable and non-permeable sections is analyzed regarding its capability to reduce fouling caused by filter cake formation.

# Crystals, Defects and Glasses of Compressible Microgels

**Alberto Fernandez-Nieves**

*School of Physics, Soft Condensed Matter, Georgia Institute of Technology*

[alberto.fernandez@physics.gatech.edu](mailto:alberto.fernandez@physics.gatech.edu)

Crystallization is often suppressed by the presence of large point impurities. Surprisingly, microgels can overcome this limitation: Large microgels can spontaneously deswell to fit into the crystal lattice of smaller but otherwise identical microgels. In neutral pNIPAM microgels, which nevertheless possess a peripheral charge, a difference in osmotic pressure between the inside and outside of the particles develops when the associated counterion clouds of neighboring particles overlap. When this  $\Delta\Pi$  approximately exceeds the bulk modulus of the softest and largest microgels, these deswell, enabling crystallization. Noteworthy, similar osmotic pressure effects can also manifest in suspensions that remain liquid-like on their approach to the glass, pushing the glass transition to very high particle number densities. Our results indicate that particle compressibility, as manifested via deswelling, fundamentally changes the role of particle density and polydispersity by enabling crystallization or preventing glass formation of suspensions that would unavoidably become disordered solids.

# Hierarchical Mechanics and Assembly in Hydrogels

**Peter Yunker**

***School of Physics, Soft Matter of Life and Death, Georgia Institute of Technology***

[pyunker3@gatech.edu](mailto:pyunker3@gatech.edu)

Hierarchical structures are abundant, ranging from biological materials like collagen, to engineered structures like the Eiffel tower, to suspensions of hydrogel particles. In such suspensions, cross-linked gels form micron-sized particles, which are then assembled into larger structures. The final mechanical properties of the suspension depend on structural characteristics on both gel- and particle-length-scales. In this talk, I will discuss a bottom-up approach to understand how structural hierarchy affects mechanics, as well as assembly techniques that take advantage of the hierarchical nature of hydrogel particles.

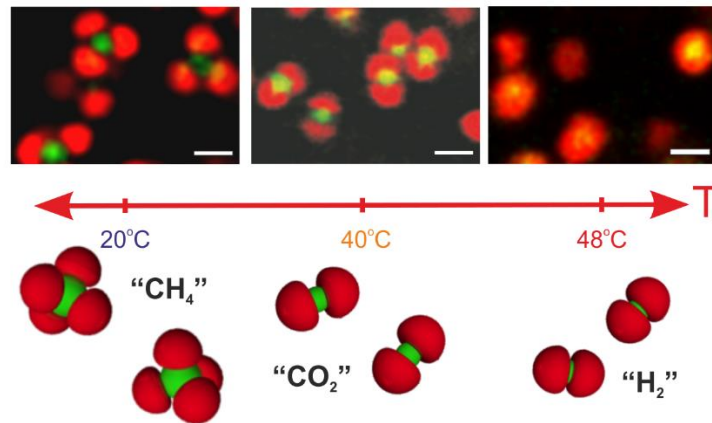
# Self-Assembly of Microgels

Jérôme J. Crassous

*Institute of Physical Chemistry, RWTH Aachen University*

[crassous@pc.rwth-aachen.de](mailto:crassous@pc.rwth-aachen.de)

Responsive microgels are cross-linked polymeric networks swollen by solvent that respond to diverse stimuli such as pH, temperature or the application of external fields. We focus on thermoresponsive poly(N-isopropylacrylamide) (PNIPAM) and poly(N-isopropylmethacrylamide) (PNIPMAM) microgels presenting a volume phase transition temperature marking the transition from a swollen to a collapsed state. This property allows to control not only the size but as well the interactions of the particles from long range soft repulsive to short range attractive making them ideal model systems to investigate many Soft Matter questions including colloidal crystallization, glass and jamming transition and gels formation. We illustrate the different self-assembly strategies using composite core-shell microgels consisting of a polystyrene core surrounded by a thermoresponsive shell. The latter core further allows for the particle nanoengineering into different shapes that enlarges the scope of microgels to anisotropic systems which size, shape, angularity and interactions can be controlled with the temperature. Hereby, using complementary shapes allows for instance to implement selective and specific lock and key self-assembly and build up responsive colloidal molecules as colloidal analogs to adaptive chemistry. Finally, we discuss the application of homogeneous and heterogeneous electric fields to direct the self-assembly process.



Confocal micrographs of responsive lock- and key- particles assembled into colloidal molecules with tunable valence. Scale bars: 1  $\mu\text{m}$ .

# Electrochemistry of Microgels

Felix Plamper

*Institute of Physical Chemistry, RWTH Aachen University*

[plamper@pc.rwth-aachen.de](mailto:plamper@pc.rwth-aachen.de)

Microgels have often the ability to undergo a volume phase transition with respect to environmental changes, allowing an adjustment of segmental proximity and network dynamics [1]. Introduction of charges into the microgel network leads to a possible interaction of the polyelectrolyte microgel with oppositely charged counterions based on electrostatic attraction (host-guest interplay). In case of redox-active counterions, the charge of these guest molecules can be changed by electrochemical means [2].

Hence, we address thermoresponsive cationic microgels and their influence on the electrochemistry of hexacyanoferrates [3]. Further, we investigate the influence of the counterion guests on the swelling of the microgel hosts: the size of the cationic microgel can be reversibly modulated by electrochemical switching leading to a redox-responsive microgel system [4].

Finally, also other attempts to generate electroactive microgel colloids (e.g. with permanently linked redox-active units) are discussed.

[1] Maccarrone, S., Mergel, O., Plamper, F. A., Holderer, O. and Richter, D. (2016). Electrostatic Effects on the Internal Dynamics of Redox-Sensitive Microgel Systems. *Macromolecules* 49, 1911.

[2] Plamper, F. A. (2015). Changing Polymer Solvation by Electrochemical Means: Basics and Applications. *Adv. Polym. Sci.* 266, 125.

[3] Mergel, O., Gelissen, A. P. H., Wünnemann, P., Böker, A., Simon, U. and Plamper, F. A. (2014). Selective Packaging of Ferricyanide within Thermoresponsive Microgels. *J. Phys. Chem. C* 118, 26199.

[4] Mergel, O., Wünnemann, P., Simon, U., Böker, A. and Plamper, F. A. (2015). Microgel Size Modulation by Electrochemical Switching. *Chem. Mater.* 27, 7306.



# Programmable Matter: Shape Shifting 3D Printed Polymer Gels

Elisabetta Matsumoto

*School of Physics, Georgia Institute of Technology*

[sabetta@gatech.edu](mailto:sabetta@gatech.edu)

Liquid crystal elastomers have long been one of the most powerful materials capable of programmable shape change [1, 2]. Recent advances have enabled the pixel-level control over the director field [3]. Likewise, nematic order in the cellulose within plant cell walls leads to a wide variety of nastic motion in many species [4]. With botanical inspiration, we have demonstrated the ability to control the local director field in an elastomer with macroscopic nematic order using a 3D printing technique [5]. The nematic order, obtained through shear alignment of the cellulose fibrils within the deposition tip, directs an anisotropic elasticity and, consequently, anisotropic swelling response.

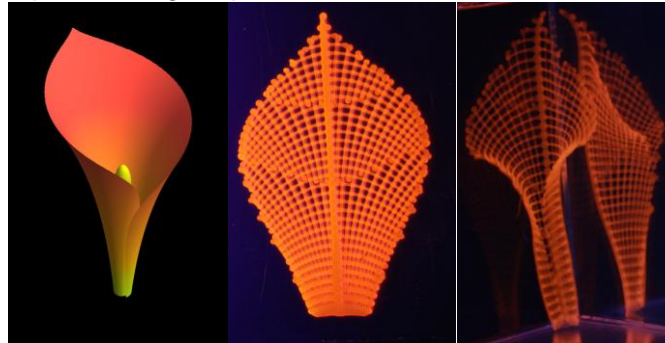


FIG. 1: The nematic director field, parallel to the printed fibres, directs an anisotropic swelling response, which leads to programmable shape change.

Here, we present a model which combines nematic order with anisotropic elasticity to address the programmability of this system. Programmable shape change relies upon the ability to control both Gaussian and mean curvature independently. Encoding nematic order is tantamount to inscribing a set of metric deformations into the elastomeric membrane. Gauss's Theorema Egregium relates in-plane gradients and curvatures in the metric to Gaussian curvature of the final object [6]. Yet this is not enough to distinguish between isometric embeddings. With the inclusion of the elastic theory of anisotropic plates coupled with a hidden broken symmetry, controlling not only the magnitude, but the sign, of mean curvature becomes possible. This explicit construction makes the inverse problem tractable: how might we design local anisotropies to reproduce a specific structure. Additionally, we put forward a new method of using pre-existing liquid crystal elastomer technology to incorporate mean curvature control at the pixel level.

[1] Warner, M., Modes, C. D. & Corbett, D. Proc. Roy. Soc. A, 466, 2975 (2010).

[2] de Haan, L. T. et al. Angew. Chem., 51, 12469 (2012).

[3] Ware, T. H. et al. Science, 347, 982 (2015).

[4] Burgert, I. & Fratzl, P. Phil. Trans. Roy. Soc. A, 367, 1541 (2009).

[5] Gladman, A. S., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L. & Lewis, J. A. Nature Materials, advanced online publication (2006).

[6] Aharoni, H., Sharon, E. & Kupferman, R. Phys. Rev. Lett., 113, 257801 (2014).

# The Extreme Thermodynamics of Polymer Gels

**Mike Dimitriyev**

*Physics, Georgia Institute of Technology*

[mdimitriyev3@gatech.edu](mailto:mdimitriyev3@gatech.edu)

Polymer gels are soft materials that can undergo large volume changes when in equilibrium with a solvent bath. For suitably prepared gels, there is a discontinuous transition between distinct swollen and deswollen phases. The ability to actuate large deformations in response to modest changes in solvent quality, e.g. via variations in temperature, has made polymer gels prolific materials in extreme mechanics. However, this behavior relies on slow, quasistatic changes in the environment of the polymer gel. The response of a gel under rapid heating, for example, is not well understood. We consider swollen polymer gels that are rapidly heated through the deswelling phase transition. Rather than deswelling, the gel maintains a fixed volume, due to the presence of a polymer-dense skin that forms at the boundary of the gel. Out of equilibrium with the surrounding solvent bath, the gel instead undergoes internal phase-separation, forming coexistent solvent-rich and solvent-poor regions. This new equilibrium is also characterized by shape change: for example, a polymer gel prepared in the shape of a torus may buckle into a "Pringle"-like shape, whilst remaining at a constant volume. Interestingly, these large deformations are achieved via thermodynamic instability, i.e. by passing through a phase transition, rather than by mechanical instability. Our results are suggestive of achieving effects of extreme mechanics through "extreme thermodynamics."

## 1) Anisotropic self-assembly of isotropic colloidal building blocks

**Marcel Rey**

*Mechanical Process Engineering at the Friedrich-Alexander-University Erlangen-Nuremberg*

[marcel.rey@fau.de](mailto:marcel.rey@fau.de)

We study the self-assembly of two-dimensional core-shell particles at an air/water interface. As predicted by Jagla almost two decades ago, such core-shell particles can show a complex phase diagram including non-intuitive phases like square and chain packing. We found these structures experimentally using a Langmuir trough. Upon increasing pressure, we see a transition from hexagonal non-close packed to chain packing, then to square packing and at high pressure to hexagonal close packing.

## 2) Towards a surface-bound microgel system using DNA-hybridization and super resolution fluorescence microscopy

**Laura Hoppe-Alvarez**

*Spectroscopy of Condensed Matter at the RWTH Aachen*

[hoppe.alvarez@pc.rwth-aachen.de](mailto:hoppe.alvarez@pc.rwth-aachen.de)

The past decade has witnessed remarkable development in the synthesis of microgels with specific characteristics. Their stimuli-responsive swelling properties opened a large field of applications such as drug delivery systems. The development of appropriate applications is highly dependent on the fundamental understanding of the molecular properties and structures of such microgels. Our goal is to build a surface-bound microgel system, which allows us to visualize microgels in their native state using modern super-resolution fluorescence microscopy techniques. Our approach for such a surface-immobilization takes advantage of the high resolution to write structures with chemical e-beam lithography (C-EBL) and its combination with optical photolithography. Furthermore, our goal is the hybridization of microgels to DNA-strands immobilized to specific spots on the patterned surface. We could already show how to localize individual spots in the C-EBL pattern in different microscopes (electron and optical) and developed appropriate software routines to address them individually. We were able to successfully attach fluorescently labeled DNA strands to spots in the C-EBL pattern. The next step will include the hybridization of DNA-functionalized microgels to the DNA-strands on the surface. Modern super-resolution fluorescence techniques such as DNA-PAINT will be used in order to image three-dimensional microgel structures.

### **3) Swelling of a responsive network within different constraints in multi-thermosensitive nanogels**

**Monia Brugnoni**

*Physical Chemistry II at the RWTH Aachen*

[brugnoni@pc.rwth-aachen.de](mailto:brugnoni@pc.rwth-aachen.de)

Silica-core double-shell and the corresponding hollow nanogels made of two polymeric shells are studied. The swelling of the shells can be tuned by temperature changes enabling swelling states above, below and between the distinct volume phase transition temperatures of the two polymers. This enables to investigate the effect of different constraints on the swelling of the inner network. Small-angle neutron scattering with contrast variation in combination with computer simulation disclose how the expansion of the inner shell depends on its constraints.

## 4) PEGylated PNIPAM microgels: synthesis and solution behavior

**Julien Es Sayed**

*Soft Matter Engineering and Science Laboratory at ESPCI Paris*

[julien.es-sayed@espci.fr](mailto:julien.es-sayed@espci.fr)

During the last three decades, microgels have received considerable interest for applications in a diverse range of areas including material science, drug delivery, biosensors... Microgels are defined as colloidal gel particles of approximately 0.05 to 1  $\mu\text{m}$  exhibiting network structure that swells in a suitable solvent. Research has been directed towards the synthesis «stimuli-responsive» or «smart» microgels whose properties can be modulated reversibly in response to an environmental stimulus such as pH, temperature, light, ... In order to be used in the above cited applications, microgels need both to be functionalizable and to exhibit a high colloidal stability. To achieve this, thermoresponsive microgels were synthesized by surfactant-free precipitation polymerization of NiPAM in presence of poly(ethylene glycol) methacrylate with hydroxyl end-group (PEGMAOH) and a chemical crosslinker, methylene-bis-acrylamide (MBA). Combining techniques such as DLS,  $^1\text{H}$  NMR,  $\mu\text{DSC}$ , SEM, zetametry and tensiometry we show that (i) incorporation of the PEGMAOH in the synthesis enables to control precisely the size and the polydispersity of the microgels; (ii) the incorporated PEG chains do not change the Volume Phase Transition Temperature (VPTT) of the synthesized microgels; (iii) PEG chains are mainly localized within the microgel outskirts which provides them a highly colloidal stability in aqueous solution.

## 5) Enzymatic synthesis of aqueous microgels with glucose oxidase

Elisabeth Gau

*DWI – Leibniz Institute for Interactive Materials*

[gau@dwil.rwth-aachen.de](mailto:gau@dwil.rwth-aachen.de)

In recent years, growing attention in the field of macromolecular sciences has been paid to aqueous, stimuli-responsive microgels, since they are promising candidates for numerous biomedical applications. Precipitation polymerization is the most frequently used method for the synthesis of aqueous microgels. Conventionally used initiators are azo- or peroxide-based compounds, which are cleaved into radicals by heat. Thus, the incorporation of thermally instable compounds like biomolecules is not possible.[1] A promising alternative to overcome this drawback is enzyme-initiated polymerization, since enzymes are highly active at moderate temperatures. In this work, we present the use of a glucose oxidase-based initiator system for the enzymatic synthesis of aqueous microgels. Glucose oxidase (GOx) catalyzes the oxidation of  $\beta$ -D-glucose with molecular oxygen to D-glucono-lactone and hydrogen peroxide. Through the addition of ferrous ions ( $\text{Fe}^{2+}$ ), the hydrogen peroxide is cleaved into hydroxyl radicals. These radicals act as initiators for the polymerization reaction.[2] Microgels based on different biocompatible monomers like the thermo-responsive *N*-vinylcaprolactam (VCL)[3] and oligo ethylene glycol acrylates (OEGAs) were synthesized. The polymerization kinetics were monitored with online-calorimetry and the influence of different parameters like initiator and crosslinker amount and the reaction temperature on the microgels were investigated. Besides, it was found that parts of the enzyme get immobilized into the microgel networks during polymerization, showing still high activity after the reaction. This encapsulation of GOx can be used to generate core-shell microgels in a facile way without addition of new enzyme. In general, the GOx-based initiatorsystem is a very promising alternative to conventional initiators for microgel synthesis, enabling polymerization at moderate temperatures and thus incorporation of biomolecules into polymers.

[1] Pich et al., *Adv. Polym. Sci.* 2011, 234, 1-37.

[2] Johnson et al., *Biomacromolecules* 2009, 10, 3114-3121.

[3] Gau et al., *Green Chemistry* 2018, 20, 431-439.

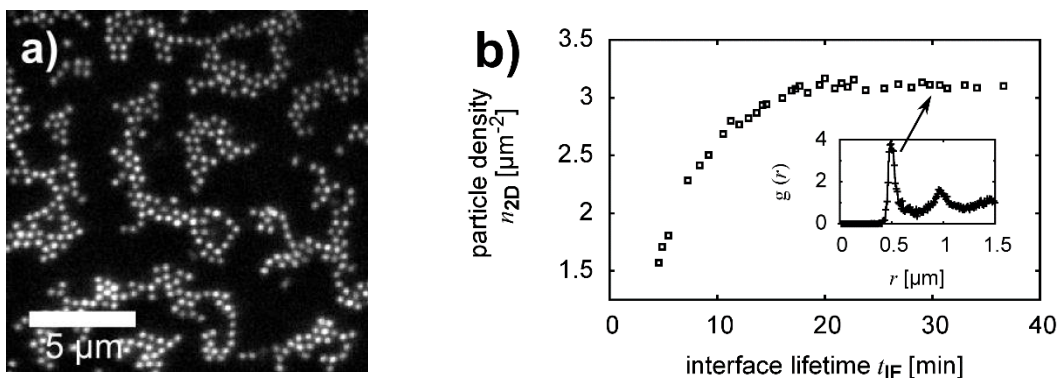
## 6) Fluorescence microscopy investigation of microgels at interfaces

Eric Siemes, Miriam Faulde

*Spectroscopy of Condensed Matter and Fluid Process Engineering at RWTH Aachen*

[siemes@pc.rwth-aachen.de](mailto:siemes@pc.rwth-aachen.de), [miriam.faulde@avt.rwth-aachen.de](mailto:miriam.faulde@avt.rwth-aachen.de)

Unlike most ordinary colloids, microgels have a soft cross-linked polymer structure which allows them to deform significantly. Particularly at interfaces, this is an advantage, since e.g. emulsions can be efficiently stabilized. Due to the incorporation of stimuli-responsive comonomers, these emulsions can be destabilized on demand, leading to a controlled coalescence of the droplets. The observation of microgel arrangement at the interface and the elucidation of their structure is currently predominantly performed with indirect methods such as AFM, Langmuir trough or Freeze-fracture shadow-casting (FreeSCA) cryo-SEM. We present modern high-resolution Fluorescence Microscopy techniques which allow us to position and track the microgels in situ at liquid/liquid interfaces and additionally to investigate their structure by superresolution. Our current results allow us to dynamically measure the saturation of an interface over time, and further to obtain information on the diffusion behavior of individual microgels. Moreover, the temporal change in radial distribution function reveals information about the evolution of structural order of microgels at a liquid-liquid interface.



a) Diffraction limited fluorescence microscopy image of NIPAM-based microgels at decane/water-interface, revealing a cluster-like arrangement of microgels.

b) Increasing particle density at 23  $^{\circ}\text{C}$  at the decane/water-interface as a function of interface lifetime. Inset: Radial distribution function revealing an ordered structure.



## **7) Stiffness, fracture mechanics and error tolerance of hierarchical elastic networks**

**Jonathan Michel**

*Physics at the Georgia Institute of Technology*

[jmichel6@gatech.edu](mailto:jmichel6@gatech.edu)

Structural hierarchy, in which materials exhibit organization on multiple, disparate length scales, is ubiquitous in biological tissues, a common architectural strategy, and an increasingly prevalent feature of man-made materials. In all these cases, a common structural motif is a network of interconnected beams or filaments. While filamentous materials with one important length scale have been well studied, and special cases of hierarchical materials have been treated in the literature, we perceive a lingering need for a general framework for understanding the interplay of structures on varying length scales, and how each scale contributes to a material's overall properties. We present results of normal mode analysis and tensile tests of filamentous networks with a diluted triangular lattice structure on two and three distinct scales. We validate a simple scaling law for the dependence of stiffness on connectivity on each scale, and find that the smallest scale sets the vibrational density of states, while larger scales are important for suppressing low-energy, bending-dominated deformations. We finally discuss the robustness of hierarchical materials to random errors in assembly.

## 8) Microgel engineered enzymatic and chemical reactions – towards tandem catalysts

**Maximilian Nöth, Islam Elawaad, Mehdi D. Davari**

*Biotechnology at the RWTH Aachen*

[m.noeth@biotec.rwth-aachen.de](mailto:m.noeth@biotec.rwth-aachen.de), [elawaad@dwj.rwth-aachen.de](mailto:elawaad@dwj.rwth-aachen.de),  
[m.davari@biotec.rwth-aachen.de](mailto:m.davari@biotec.rwth-aachen.de)

Enzymes as biocatalysts are generally able to catalyze reactions with high substrate-, regio- and enantioselectivity, but often lack in the required resistance towards organic solvent to be used in chemical synthesis. In comparison chemical catalyst exhibit excellent stability in organic solvent, but often lack in selectivity. The combination of bio- and chemo-catalysts in a cascade reaction would combine their intrinsic advantages. However, the reaction setup would be challenging because of the opposing demands to the reaction conditions. Microgel polymers offer promising interfaces that could bring both catalysts in close proximity, while keeping each in its preferred environment. Hydrophilic microgels can mimic the “natural” environment of an enzyme and protect it against the harsh reaction conditions required for chemical catalysis. Here, we pursue the combination of an engineered cytochrome P450 BM3 variant capable of performing aromatic hydroxylation on substituted benzenes together with a copper scorpionate catalyst for subsequent C-C or C-O couplings. Different approaches are examined for the efficient enzyme immobilization on hydrophilic microgels, mainly focusing on the formation of covalent bonds as well as electrostatic interaction between the enzyme and the microgel. By now we have successfully immobilized the aforementioned P450 BM3 variant in PVCL and PNIPAM based microgels through electrostatic interactions. The main challenge of the immobilization strategy is to find the correct balance between the residual activity of the immobilized enzyme and the stability against organic solvents.

## 9) Polyampholyte microgels as ionic traps for guest molecules

Wenjing Xu

*Functional and Interactive Polymers at the RWTH Aachen*

[xu@dwf.rwth-aachen.de](mailto:xu@dwf.rwth-aachen.de)

Polyampholyte microgels as container systems to entrap guest molecules like proteins, dyes or nanoparticles has been intensively studied in the past years and has also won great attention in the field of biomedical application. These kind of smart materials are extremely interesting due to their facile functionalization and their high biocompatibility. Additionally, the functionality of such microgels can be controlled by the applied monomers and crosslinker density during the synthesis. In this way the properties of the particles and the response to outer stimuli can be tuned. Guest molecules in particular proteins tend to attach into microgel systems through chemical- (covalent) or physical- (electrostatic) binding. The latter one has attracted more attention since it offers the opportunity to achieve an efficient binding and triggered release in the surrounding medium via electrostatic interactions [1]. In this content we aimed to synthesize polyampholyte microgels with different structures (random distribution of ionizable groups, core-shell distribution of ionizable groups and Janus-like microgels). Furthermore, the influence of outer stimuli (pH, temperature, salt concentration and different medium) to the interaction between the model protein cytochrome c and the synthesized microgels was studied. In addition, we demonstrate that the distribution of the ionizable groups in the microgels (random vs core-shell) also has a strong influence to the release procedure of the proteins. Once the proteins were entrapped inside the microgel containers at pH 8 by electrostatic attraction forces (protein and microgels are oppositely charged at pH 8), they remain strongly bound and show no leaching effects for months. An effective triggered release can be achieved by variation of the pH value (from pH 8 to pH 3, protein and microgels are equally charged at pH 3) of the surrounding medium.

[1] S.V. Vinogradov, T. K. Bronich and A. V. Kabanov, *Adv. Drug Deliv. Rev.*, 2002 (54), 135.

## 10) Dynamically-crosslinked self-assembled thermoresponsive microgels with homogeneous internal structure

**Eva Mueller**

*Chemical Engineering at the McMaster University*

[muellee@mcmaster.ca](mailto:muellee@mcmaster.ca)

Conventional poly(*N*-isopropylacrylamide) (PNIPAM) microgels prepared via precipitation polymerization have been used in many applications. However, in the context of practical biomedical use in vivo, the lack of degradability of conventional PNIPAM microgels creates challenges in that conventional microgels cannot be cleared effectively from the body. In response, we have developed a self-assembly method in which well-defined hydrazide and aldehyde functionalized PNIPAM oligomers are used to form microgels linked by hydrolytically degradable hydrazone crosslinks. Interestingly, while conventional microgels have a dense core/diffuse shell structure due to the faster polymerization rate of the crosslinker used, a combination of surface force measurements, small angle neutron scattering, and ultrasmall angle neutron scattering confirmed that these self-assembled microgels have a homogeneously cross-linked internal structure. This somewhat surprising result is attributed to a combination of the dynamic nature of the hydrazone crosslinking chemistry and the assembly conditions used that promote polymer interdiffusion. Coupling the predictable diffusive and refractive properties enabled by the homogeneous internal structure with the degradability enabled by the assembly chemistry, we anticipate that these microgels offer opportunities to address challenges in drug delivery, biosensing, and optics.

## 11) Synthesis of micron-sized poly(*N*-vinylcaprolactam) microgels by temperature-ramp polymerization

**Agnieszka Ksiazkiewicz**

*Functional and Interactive Polymers at the RWTH Aachen*

[ksiazkiewicz@dwi.rwth-aachen.de](mailto:ksiazkiewicz@dwi.rwth-aachen.de)

Microgels are cross-linked polymer networks that can respond to environmental change like temperature or pH. When triggered, they collapse or swell in a solvent, preserving their 3D structure. Micron-sized microgels can have plenty of interesting applications in crystallization studies, microlensing or mimicking cells. Microgels with size above 10  $\mu\text{m}$  can be synthesized using microfluidics [1]. However, very low yields and specific equipment requirements lead to high demand on synthesis of microgels via dispersion polymerization approaches. Moreover, the typical size of micro/nanogels synthesized using standard batch polymerization reactions is in nanometer scale. Thus particles ranging from 1 to 10  $\mu\text{m}$  are not easily reachable and means to obtain them need further investigation. For the first time, we have synthesized temperature-responsive poly(*N*-Vinylcaprolactam) (pVCL) microgels with large diameter (1-10  $\mu\text{m}$ ) via aqueous, surfactant-free precipitation polymerization. The size control was achieved by employing programmed temperature ramp during the nucleation stage of polymerization. Micron-sized poly(*N*-Isopropylacrylamide) (pNIPAm) microgels have been obtained previously [2], however known toxicity and suspected cancerogenicity of pNIPAm disqualifies the usage of these gels in medical applications. In contrast to pNIPAm, pVCL is non-toxic and biocompatible [3], making it a great candidate in medical and biomaterial fields. In this work, the influence of various parameters such as monomer, cross-linker and initiator concentration, rate of temperature ramp, start and end temperature as well as dosing of the reagents was investigated. We were able to obtain microgels in different size ranges, depending on parameters altered. To best characterize such big but soft particles, laser diffraction particle sizing technique as well as confocal microscopy were utilized. Consequently, this study hopes to give more insight and understanding about the formation mechanism of larger pVCL microgels. For this purpose, in-situ dynamic light scattering measurements as well as in-line reaction calorimetry, where heat flow of the reaction can be monitored, were carried out.

[1] Shah R. K., Kim J., Agresti J. J. and Chu L. *Soft Matter* 4 (2008) 2303–2309.

[2] Meng Z., Smith M. H. and Lyon A. *Colloid and Polymer Science* 287 (2009) 277-285.

[3] Vihola H., Laukkanen A., Valtola L., Tenhu H and Hirvonen J. *Biomaterials* 26 (2005) 3055–3064.

## 12) Shaping microgels in simulations

**Andrea Ninarello**

*Complex Systems at the Sapienza University of Rome*

[andrea.ninarello@roma1.infn.it](mailto:andrea.ninarello@roma1.infn.it)

Recent experimental studies observed that the synthesis process influences non-trivially the microgel topology. The largely employed PNIPAM microgels were found to display a non-homogeneous dense core surrounded by a sparse corona. Whereas, in absence or low concentration of crosslinkers, a new class of microgels was produced, the so-called ultrasoft microgels, that show an inverted density profile, with a dense outer corona. In this contribution we generate microgels particles in computer simulations by means of a self-assembly protocol. We obtain a disordered network where patchy particles represent polymer monomers and crosslinkers. We target specific density profiles by introducing additional forces during the assembly process acting on both monomers and crosslinkers. This technique allows for the implementation of realistic microgels in a computer simulation that are able to mimic experimental equivalents both on a microscopic scale as well as for topological, swelling and elastic properties.

## 13) Concentration-dependent de-swelling effects on structural and dynamic properties of ionic microgel suspensions

**Mariano Brito**

*Institute of Complex Systems, ICS-3, Forschungszentrum Jülich GmbH*

[m.brito@fz-juelich.de](mailto:m.brito@fz-juelich.de)

Ionic microgels are highly sensitive to changes in environmental conditions. This allows for controlling their size and effective interactions by adjusting the temperature, solvent quality, degree of polymer cross-linking, suspension ionic strength and particle concentration. In this work, we study theoretically the influence of the concentration-dependent de-swelling of weakly-crosslinked ionic microgels on structural and dynamic suspension properties. Our analysis is based on an effective interaction potential for ionic microgels derived by Denton [1], where we consistently introduce the de-swelling effect using the Denton-Tang method to compute the equilibrium microgel size [2]. Using the effective interaction potential, we compute pair correlation functions and static structure factors, which in turn are used as input for the calculation of dynamic suspension properties. The latter include hydrodynamic functions, collective diffusion coefficients, and the low- and high-frequency viscosities. We present and discuss results for the dependence of structural and dynamic properties on salt and microgel concentrations and on bare microgel charge.

[1] A. R. Denton, Phys. Rev. E 67, 011804 (2003).

[2] A. R. Denton and Qiyun Tang, J. Chem. Phys. 145, 164901 (2016).

## **14) Tunable thermoresponsive building blocks for versatile applications**

**Dirk Rommel**

*DWI – Leibniz Institute for Interactive Materials*

[rommel@dwj.rwth-aachen.de](mailto:rommel@dwj.rwth-aachen.de)

Free radical polymerization is used to prepare thermoresponsive polymers exhibiting lower critical solution temperatures (LCST) in aqueous solution. These switchable properties allow the production of smart materials.

The relatively low speed of free radical polymerization holds disadvantages in the production of more complex product geometries in microfluidics.

The synthesis of defined, thermoresponsive star oligomers with N-terminated functional groups allows the utilization of faster and more robust reaction mechanisms and thus enables the construction of anisometric structures using these versatile building blocks.

In this study we present the synthesis and application of defined thermoresponsive star polymers with tunable arm lengths, LCSTs and N-terminated functional groups.



## 15) Investigations of the internal structure of hollow charged microgels by SANS

**Sarah Turnhoff**

*Physical Chemistry II at the RWTH Aachen*

[turnhoff@pc.rwth-aachen.de](mailto:turnhoff@pc.rwth-aachen.de)

Hollow microgels have the potential to meet one of the key challenges in biomedical research: The design of nano-carriers allowing for triggered uptake, storage and release of drugs. Small-angle neutron scattering (SANS) was already used to study the internal structure of hollow doubly temperature-sensitive microgels. Based on the temperature-dependent swelling behavior of poly(*N*-isopropylacrylamide) (PNIPAM) based microgels, the size of the void changes when changing the temperature. Introduction of charges into the polymeric network improves the swelling properties of microgels due to the repulsion of similar charges and the increased osmotic pressure within the gel network. In this work, we address the synthesis of hollow charged microgels and the investigation of their properties as a function of charge density and ionic strength of the solvent. NIPAM is copolymerized with dimethylitaconate (DMI) onto sacrificial silica cores in a seed and feed precipitation polymerization. Sodium hydroxide is used to etch the silica and to saponify the DMI to itaconic acid introducing negative charges into the shell. Potentiometric titrations, electrophoretic mobility and different scattering techniques are used to analyze the pH-dependent behavior of charge density and microgel size. Furthermore, SANS is used to prove the persistence of the void below and above the volume phase transition temperature. Additionally, the suppression of the temperature-sensitive collapse of the shell due to the presence of charges is demonstrated.

## **16) Rapidly self-assembled, hydrophobically-modified poly(oligoethylene glycol methacrylate)-based nanogels for the delivery of poorly water-soluble therapeutics**

**Madeline Simpson**

*Chemical Engineering at the McMaster University*

[simpsomj@mcmaster.ca](mailto:simpsomj@mcmaster.ca)

Nanogels are advantageous drug carriers because their chemical and physical properties can be tuned to improve drug uptake, target specific tissues or cell types, control drug release and ultimately decrease the quantity of therapeutic required for effective intervention. However, many conventional nanogels do not easily degrade, a key barrier for use in biomedical applications. To address this concern, we have designed a rapid, thermally-driven self-assembly method to produce nanogels (hydrogel-based nanoparticles) composed of well-defined linear hydrazide and aldehyde-functionalized poly(oligoethylene glycol methacrylate) (POEGMA)-based precursor polymers that create stable nanogels cross-linked by covalent, but hydrolytically degradable, hydrazone bonds. This self-assembly method produces nanogels ~200 nm in size with low polydispersity. Loading of olanzapine, an atypical antipsychotic drug used in the treatment of schizophrenia and bipolar disorder, occurs with encapsulation efficiencies up to 70%. These self-assembled nanogels are also able to mechanically deform, which can aid transport through tight junctions, such as the blood-brain barrier, or into cells. The POEGMA-based system also enables long circulation times as the protein-repellent nature of the polymer helps to avoid biological clearance mechanisms. This facile self-assembly method demonstrates significant potential for efficient drug delivery to the brain.

## 17) Monte Carlo simulations of weak polyelectrolyte microgels: pH-dependence of conformation and ionization

**Cornelius Hofzumahaus**

*Physical Chemistry II at the RWTH Aachen*

[hofzumahaus@pc.rwth-aachen.de](mailto:hofzumahaus@pc.rwth-aachen.de)

Weak polyelectrolyte microgels are three-dimensionally cross-linked polymer networks of colloidal dimension exhibiting acidic or alkaline groups. In dependence of the pH of a surrounding medium, their degree of ionization changes. This change of the degree of ionization is accompanied by a volume change of the polymer network, which can be attributed to electrostatic and osmotic pressure contributions. The mutual interconnection of likewise-ionizable groups into one macromolecule leads to a suppression of the degree of ionization as compared to the ionizable monomer at infinite dilution. The shift of the effective pK<sub>A</sub>-value is commonly known for weak polyelectrolytes and can be explained by the increasing additional free energy cost for ionization due to the spatial proximity already ionized groups. In this contribution, we investigated the conformation and ionization behavior of a weak polyelectrolyte microgel with acidic functionalization. The polymer network was modeled as a bead-spring network within the framework of the primitive model for polyelectrolytes. The model system was examined by means of Monte Carlo simulations on a coarse-grained level and the protonation/deprotonation was explicitly included in the simulations using a titration Monte Carlo move. Upon variation of the pH, a transition between a neutral, unswollen network and a highly charged and swollen network can be found. Our simulations showed a pronounced suppression of the pH-dependent ionization as compared to the ideal titration behavior. We found an inhomogeneous distribution of the degree of ionization along the radial profile of the polymer network. In addition to the investigation of a reference network, the influence of the cross-linking density, the relative content of titratable monomers and the polymer volume fraction was investigated.

## 18) Modeling kinetics and non-linear micromechanics of hydrogels using dissipative particle dynamics

**Svetoslav Nikolov**

*Complex Fluids Modeling and Simulation at the Georgia Institute of Technology*

[snikolov3@gmail.com](mailto:snikolov3@gmail.com)

When exposed to an appropriate external stimulus microgels are capable of undergoing large and reversible changes in volume which has made them attractive as microscopic actuators and drug delivery agents. However, the mechanics of microgels near the volume-phase transition is still not well understood. Full-scale atomistic modeling of micrometer-sized gel networks is currently not possible due to the large length and time scales involved. We develop a mesoscale model based on dissipative particle dynamics to examine the mechanics of microgels in solvent. We vary the osmotic pressure of the gels in order to probe how the bulk modulus of our gels changes for different solvent conditions. We fit our bulk modulus data to Flory-Rehner's theory and show that our model is in good agreement with the theory. By looking at the swelling kinetics of our gels we also find that, during swelling, microgels preserve a homogeneous internal structure, whereas deswelling leads to the formation of chain bundles and network coarsening.

## 19) A catalyst-free, thermal gelation system for micro fabrication technologies

**Andreas Krüger**

*DWI – Leibniz Institute for Interactive Materials*

[krueger@dwf.rwth-aachen.de](mailto:krueger@dwf.rwth-aachen.de)

A catalyst-free, thermal gelation system is developed to produce anisometric functional microgels with adaptable mechanical properties and self-assembly behavior.

Liquid star-shaped poly(ethylene oxide-stat-propylene oxide) polymers are functionalized with amine and epoxy moieties to enable a simple click chemistry as gelation mechanism via thermally induced crosslinking in aqueous solution. In order to characterize the hydrogels, physical and mechanical properties are investigated in relation to the prepolymer concentration, heating duration and gelation temperature. To prepare microgels with an in-mold polymerization technique, the reactive polymer solution was mixed with short ethylene oxide as non-inert filler. This filler replaces water as solvent and avoids premature evaporation inside the micron-sized cavities without participating in the crosslinking reaction. After filling the cavities in the molds with the prepolymer mixture, gelation is performed by heating the sample in an oven at different temperatures. Indicated by STED microscopy, the microgel rods exhibit highly homogeneous microporosity, which differs significantly to previously reported double networks formed via reaction-induced phase separation in the case of acrylate based poly(ethylene oxide-stat-propylene oxide) networks. Moreover, the microgels self-assemble in aqueous solution forming either random or precisely stacked aggregates as a function of the microgel stiffness.

## **20) Prototyp design of a miniaturized static light scattering cell for in-line monitoring of microgel production processes**

**Luise Bering**

*Process Systems Engineering at the RWTH Aachen*

[luise.bering@avt.rwth-aachen.de](mailto:luise.bering@avt.rwth-aachen.de)

Technical applications involving functional microgels require the particles to satisfy tight specifications such as transition temperature, swelling degree and uptake volume. A controlled production process is fundamental to obtain the desired properties, but requires a sound understanding of the reaction phenomena, the determination of the state of polymerization and the possibility to manipulate and control the synthesis. Therefore, this project aims at the design and realization of a novel process analytical technology (PAT) – a probe for a comprehensive in-line characterization of microgels that is fast enough to resolve the early stages of particle formation. As a novelty, a miniaturized angularly resolved static light scattering (SLS) sensor for in-line measurements based on waveguide structures is developed. SLS allows measurement times of below one second, because it determines sizes of particles from the average intensity at multiple scattering angles instead of correlating temporal intensity fluctuations. The novel sensor will be made of a glass body with multiple integrated waveguides. The waveguides are individually structured in three dimensions using a focused femtosecond laser. To extract the particle size and distribution from the raw scattering data of the sensor, model-based calibration methods are developed.

## 21) Investigation of highly charged microgels at flat liquid-liquid interfaces

**Maximilian Schmidt**

*Physical Chemistry II at the RWTH Aachen*

[maximilian.schmidt@pc.rwth-aachen.de](mailto:maximilian.schmidt@pc.rwth-aachen.de)

Stimuli-sensitive microgels are highly interfacial active and, therefore, suitable for application as responsive emulsifiers leading to emulsions that can be broken on demand. The stability of microgel-stabilized emulsions seems to be dominated by the viscoelastic properties of the microgel-laden interface. However, the interfacial properties of microgels are far from being completely understood. Langmuir trough experiments of pH-responsive microgels revealed that the compressibility of microgels at flat liquid interfaces is not determined by direct Coulomb repulsion as microgels in the charged state could be compressed more easily than in the uncharged state. Instead, it is proposed that the different swelling of the microgel in the two states is the decisive parameter. In order to further elucidate, how electrostatics affect the interfacial properties of polyelectrolyte microgels we focus on synthesizing *N*-isopropylacrylamide (NIPAM)-based microgels with high content of itaconic acid as ionic comonomer. Each itaconic acid monomeric unit can carry up to two negative charges depending on the solution pH. The influence of pH and ionic strength of the aqueous subphase on the microgel monolayer properties is investigated at decane-water interfaces utilizing a Langmuir trough. Different types of salt are employed to control the ionic strength. Furthermore, microgel monolayers are transferred onto solid substrates and imaged via atomic force microscopy.

## 22) Understanding emergent collective biophysical behavior of platelets in blood clotting

**Yueyi Sun**

*Mechanical Engineering at the Georgia Institute of Technology*

[ysun340@gatech.edu](mailto:ysun340@gatech.edu)

Blood clotting disorders which prevent the body's natural ability to achieve hemostasis can lead to a life threatening conditions such as, excessive bleeding, stroke or heart attack. Understanding the underlying physics behind the clotting process plays an important role in developing treatment of these disorders. Since clotting is a highly complex multi scale mechanism developing a fully atomistic model is currently not possible. We develop a mesoscale model based on dissipative particle dynamics (DPD) to gain fundamental understanding of the underlying principles controlling the clotting process. In our study, we examine the influence of fibrin and platelet properties on clotting process. Through our model analysis, we discover the importance of heterogeneity of platelets within the clotting process.



## 23) Versatile nanoreactors based on temperature-responsive microgels

**Denise Kleinschmidt**

*Functional and Interactive Polymers at the RWTH Aachen*

[kleinschmidt@dwf.rwth-aachen.de](mailto:kleinschmidt@dwf.rwth-aachen.de)

Catalysis has become an essential tool for the development of sustainable industrial processes. Especially the field of homogenous catalysis has caught attention in recent chemical research due to its advantages like solubility, high reactivity and selectivity. Synthesizing such catalytic compounds is well known from literature, merely recycling and reuse of the catalysts still remains challenging. In order to solve this issue, catalysts are often immobilized on a suitable substrate. However, because of phase boundaries conventional immobilization can lead to substantial reduction of efficiency and selectivity of the catalyst. Lately, microgels have been used as substrate for catalytically active materials. In general, microgels are cross-linked, porous and mostly spherical polymer-particles which can form stable dispersions in continuous medium (e. g. in water) as these particles are permeated by the solvent (single phase system). To changes of their environment stimuli-responsive microgels respond with a collapse of the polymer-network. Consequently, microgel dispersions turn into a two-phase system. These features make stimuli-responsive microgels ideal candidates as substrate materials for homogenous catalysts. In this context we aim to combine chosen organo-catalysts with temperature-responsive microgels based on Poly-N-isopropylacrylamide forming a covalently bound microgel-catalyst. This microgel-catalyst can be used as nanoreactor for various types of reactions. Furthermore, due its temperature-sensitivity the microgel-catalyst can be recovered after the catalyzed process and be reused for further cycles of reactions.

## 24) Finite element analysis of time-developing concentration-polarization and fouling layers for cross-flow ultrafiltration in a cylindrical membrane pipe

**Gunwoo Park**

*Institute of Complex Systems, ICS-3, Forschungszentrum Jülich GmbH*

[g.park@fz-juelich.de](mailto:g.park@fz-juelich.de)

The similarity solution of a boundary layer has been frequently applied to the modeling of concentration profiles of dispersions in the case of cross-flow ultrafiltration in a cylindrical membrane pipe. The main advantage of the similarity framework is to express the advection-diffusion equation in the boundary layer as a set of ordinary differential equations with given transport properties such as the concentration-dependent diffusion coefficient and the suspension viscosity. It is a challenging task, however, to extend the similarity framework to the time development of the concentration polarization (CP) and fouling layers, especially when a complex membrane geometry is considered. In this study, we present a finite element analysis of the time-developing CP and membrane cake layers which we compare with the standard similarity solution [1]. The transport properties required as input to the finite element and similarity calculations are determined and discussed for charge-stabilized suspensions of impermeable particles[2], non-ionic microgels[3], and ionic microgels with concentration-dependent radii[4].

[1] G. W. Park, M. Brito, A. Denton, and G. Nägele, work in progress.

[2] Roa, R. et al., "Ultrafiltration of charge-stabilized dispersions at low salinity," *Soft Matter* 12, 4638–4653 (2016).

[3] Roa, R., E. K. Zholkovskiy, and G. Naegele, "Ultrafiltration modeling of non-ionic microgels," *Soft Matter* 11, 4106–4122 (2015).

[4] Brito, M. et al., work in progress.

## 25) Prediction of chain propagation rate constants in microgel synthesis systems

Leif Kröger

*Technical Thermodynamics at the RWTH Aachen*

[leif.kroeger@itt.rwth-aachen.de](mailto:leif.kroeger@itt.rwth-aachen.de)

Microgels are soft polymer particles with a wide range of possible applications, such as drug delivery system or as catalysis matrix. Studies have reported inhomogeneities regarding the crosslinker distribution inside the synthesized *N*-isopropylacrylamide (NIPAM) and *N*-Vinylcaprolactam (VCL) based microgels, which cannot be explained in detail. Hence, chain propagation rate constants are of great interest in these systems. These rate constants are difficult to obtain experimentally due to the large number of possible reactions. Furthermore, the reaction environment, i.e. polymer mass fraction, changes during the growth process, which makes an accurate experimental determination challenging. Consequently, we use quantum mechanical (QM) methods to calculate rate constants of chain propagation reactions in aqueous NIPAM and *N,N'*-methylene bisacrylamide (BIS), and in aqueous VCL and BIS systems. First the reaction rates of the polymerization are determined in the gas phase using transition state theory (TST) and Eckardt tunnelling. Afterwards, these gas phase reaction rates are updated by incorporating solvation effects based on COSMO-RS, thus providing the desired liquid phase reaction rates. Geometries and frequencies were calculated on B3LYPD3/tzvp level, while the energies were calculated on B2PLYPD3/aug-cc-pVTZ. Hindered rotor scans for the NIPAM polymerization unveiled a large number of different transition states (TS) (>6) with deep minima and different properties orthogonal to the reaction coordinate. Therefore, all reaction rates are determined for each TS separately and subsequently summed up to obtain the global reaction rate. Rate constants are calculated over a wide temperature range and for different polymer mass fractions of the solution. The obtained rate constants are compared to literature and among the two systems. Further, they are carefully analyzed regarding the microgel growth process. It will be shown that differences in the reaction rate constants are one likely source of an inhomogeneous crosslinker distribution within the resulting microgel. Finally, the presented reaction rate constants can be used by other researchers to improve their microgel growth models.

## 26) Synthesis of anisotropic hollow microgels

Anne Nickel

*Physical Chemistry II at the RWTH Aachen*

[nickel@pc.rwth-aachen.de](mailto:nickel@pc.rwth-aachen.de)

Spherical and hollow microgels, where a temperature sensitive monomer like *N*-isopropylacrylamide (NIPAm) is used for the shell synthesis, are interesting candidates for nano carriers. Given that, with a change in temperature the permeability of the shell is influenced, obtaining the possibility to store drugs inside the void. Those hollow microgels are generated via a core shell synthesis, using silica as sacrificial cores [1]. In this work, we address the challenge to create rodlike-shaped nano-carriers. Due to the more complex shape, those particles receive different diffusion properties and ordering phenomena, compared to spherical ones. Rodlike silica particles are synthesized according to the procedure of Kuijk et al. as sacrificial cores [2]. Subsequently, their surface is functionalized with 3 (trimethoxysilyl)-propylmethacrylate (MPS) to gain a reactive surface for the shell synthesis. The shell is synthesized via a seed and feed precipitation polymerization of NIPAm and *N,N'*-methylenebisacrylamide (BIS) as cross-linker. To generate hollow microgels, the core is etched in a sodium hydroxide solution. When changing the cross-linker content and the thickness of the shell, the dissolution of the anisotropic core leads to hollow microgels with different shapes compared to the silica template used. Furthermore, we see an anisotropic collapse of the microgels when heated above the volume phase transition temperature.

[1] J. Dubbert et al., *Macromolecules* 47 (2014), 8700.

[2] A. Kuijk et al., *Journal of American chemical society* 133 (2011), 2346.

## 27) A fundamental study on the interfacial interaction of organic light absorbing molecules on a metal oxide mesoporous surface

Linda Nhon

*Chemistry and Biochemistry at the Georgia Institute of Technology*

[lnhon3@gatech.edu](mailto:lnhon3@gatech.edu)

The increasing demand for clean energy (pressure to be less reliant on fossil fuel) has pushed the field of solar energy towards the development of solar fuel cells, specifically, dye sensitized photoelectrosynthesis cell (DSPEC). Unlike other solar cell devices, instead of generating electricity, DSPECs produce hydrocarbons. A key component of this device is the development of light harvesting materials (chromophores) that will co-interact with both a CO<sub>2</sub> reduction catalyst and metal oxide semiconductor to generate the redox equivalent needed to produce the desired fuel. The multifunctional processes of these chromophores distinguish them as interesting candidates to study the interfacial behavior between the organic material and metal oxide substrate. In addition to this interaction, the molecules need to be stable in aqueous solution and slightly alkaline pH. Our current work, examines this interaction at the microscale scale level; between small molecules and metal oxide colloidal units. We utilize optical spectroscopy, atomic force microscopy, and electrochemistry to understand the surface stabilization effects and interfacial charge dynamics between the chromophore and metal oxide units. Our results suggest that the organic chromophores are stable on the passivated metal oxide surface based on the observation of efficient hole injection (demonstrated through fluorescence and photocurrent work). Furthermore, our findings also suggest that to improve the charge injection efficiency between the chromophore and catalyst a non-covalent electrostatic bond (possibly an ionic bond) should form between the ionic functional units of the organic chromophores and the metal catalyst. This suggestion leads us to pursue the development of microgels with hydrophilic chains aggregating in the center and the hydrophobic core on the peripheral making these microstructures hydrodynamically stable while maintaining efficient charge transfer through the ordered spatial arrangement.

## 28) Thermo-responsive microgels at interfaces: Correlation between microgels softness and monolayer properties

**Steffen Bochenek**

*Physical Chemistry II at the RWTH Aachen*

[bochenek@pc.rwth-aachen.de](mailto:bochenek@pc.rwth-aachen.de)

Responsive microgels allow the realization of smart emulsions, which can be broken on demand. However, their interfacial properties and demulsification mechanism are not fully understood. In our study we aim to elucidate the connection between their temperature-dependent swelling (i.e. softness) and properties at liquid-liquid interfaces. We synthesized thermo-responsive poly(*N*-isopropylacrylamide) p(NIPAM) microgels and measured their interfacial properties in swollen (10 °C) and collapsed (40 °C) state. At these temperatures microgels lower the interfacial tension of water-decane interfaces to values below 20 mN/m. A Langmuir trough was used to investigate the mechanical properties of the microgel monolayer, with subsequent deposition to a substrate. With respect to the swollen microgels, the compression isotherms of collapsed microgels show an unusual one-staged course, albeit similar surface pressures. Furthermore, the collapsed microgel monolayers possess a lower compression modulus. The deposited microgels were recorded *ex situ* with atomic force microscopy (AFM). By image analysis we found structurally identical phases for both states, yet the transitions take place at different compressions. The results of cryo-SEM and ellipsometry at liquid interfaces demonstrate that their interfacial radius and height of protrusion into the non-polar phase are temperature independent, but the microgel parts situated in the aqueous phase are still thermo-responsive. As a consequence, at elevated temperatures the microgels are collapsed and the monolayer becomes more brittle. Our findings emphasize the fundamental differences between rigid and soft colloids at liquid-liquid interfaces.

## 29) Microgel arrays for regulation of cell motility and adhesion

Alexander Töpel

*Functional and Interactive Polymers at the RWTH Aachen*

[toepel@dwf.rwth-aachen.de](mailto:toepel@dwf.rwth-aachen.de)

Surface and topography chemistry are powerful tools to affect cell adhesion and migration. We used microgels as building blocks for the decoration of biointerfaces. Therefore we developed a technique that allows printing of microgels on solid substrates.[1] We successfully printed stimuli-responsive poly(*N*-isopropylacrylamide) microgels in form of colloidal arrays on glass supports with a PDMS stamp. The microgels were chemically grafted onto the glass substrates by using low-pressure Argon plasma treatment. This process led to highly stable microgel arrays in cell culture media. We could show with Liquid cell AFM investigations that surface-grafted microgels retained their swelling behavior and thermo responsiveness in aqueous media. By this technique we could also show, that extracellular matrix protein coating did not alter both their stability and topography. We demonstrated that our surface-grafted microgel arrays could serve as novel substrates for the analysis of cell adhesion and migration.[2] Microgel arrays influenced size, speed and dynamics of focal adhesions as well as cell motility forcing cells to move along highly directional trajectories. Moreover, modulation of microgel state, crosslinking density or spacing served as an effective tool for regulation of cell motility.

[1] S. Hittl, M. Schürings, A. Balaceanu, V. Mayorga, C. Liedel, A. Pich, A. Böker, *Soft Matter* 2011, 7, 8231-8238.

[2] A. S. Sechi, S. Ullmann, J. M. G. Freitas, R. P. Takehara, P. Wünnemann, R. Schröder, M. Zenke, A. Böker, G. Aydin, S. Rütten, Andrij Pich, *Adv Mater. Interf.* 2016, DOI 10.1002/admi.201600455.

### **30) Drop shape matters - Sedimentation behavior of microgel-covered single drops indicating interfacial conditions**

**Miriam Faulde**

*Fluid Process Engineering at RWTH Aachen*

[miriam.faulde@avt.rwth-aachen.de](mailto:miriam.faulde@avt.rwth-aachen.de)

Microgels have a high application potential in process engineering, one promising field of application is the liquid-liquid extraction. Here, the microgels to stabilize the rising drops and prevent coalescence and thus guarantee a uniform drop size distribution with optimal size in the column, which leads to an intensification of the process. However, the microgels also have an influence on other phenomena relevant for extraction, such as e.g. the sedimentation behavior. A detailed investigation of these phenomena is done by single drop experiments. The sedimentation behavior of single droplets is an important factor in the design of extraction apparatuses. In addition to the physiochemical properties of the solvent-system such as density and viscosity, the sedimentation behavior is significantly influenced by the nature and conditions at the interface. Here, especially the interfacial tension and mobility is crucial. Depending on the interface mobility, there are two borderline cases. On the one hand a drop with an ideally mobile interface and on the other drops that behave like rigid balls. Therefore, conclusions about the properties of the sedimentation can be drawn about the sedimentation rate. It is known that the presence of surfactants has great influence on the sedimentation behavior as these strongly influence the mobility of the interface. For the use of microgels, the influence on the interfacial mobility is of particular interest, since the polymer particles have a strong interfacial affinity. Unlike surfactants, microgels have no amphiphilic structure and therefore no clear alignment at the interface. The poster presents the generation of microgel-covered single drops as well as the influence of microgels on the sedimentation behavior and the derived interfacial properties based on experimental results and theoretical considerations.



## 31) Charged microgels at a liquid-liquid interface: computer simulation

**Alexey Gavrilov**

*Polymer and Crystal Physics at the Moscow State University*

[gavrilov@polly.phys.msu.ru](mailto:gavrilov@polly.phys.msu.ru)

It has been recently shown that microgels can effectively stabilize emulsions of two immiscible liquids. The microgels adsorbed at the interface can significantly change their shape in order to minimize the number of energetically unfavorable contacts between the liquids. In our work we address the question of how the presence of charged groups affects the behavior of microgels at a liquid-liquid interface by means of coarse-grained DPD simulations with explicit treatment of electrostatic interactions. We assume that one liquid is more polar than the other, and we utilize two models: with explicit and implicit treatment of the difference in the dielectric permittivity. We found that the microgels swelled into the more polar liquid as the amount of charged groups increased; at rather high fraction of charged groups the microgels get easily detached from the interface as it is much more favorable for them to be in the polar liquid. In addition to that, if the difference in the dielectric permittivity is treated explicitly, we observed that the liquid-liquid interface can be locally distorted by the presence of microgels which presumably decreases the electrostatic energy.

## 32) Development of glycan-functionalized microgels for scavenging of *Clostridium difficile* toxins A and B

**Sarah Boesveld, Viktoria Heine, Alexander Jans**

***Internal Medicine III at the University Hospital RWTH Aachen, Laboratory for Biomaterials at the RWTH Aachen and DWI – Leibniz Institute for Interactive Materials***

[sboesveld@ukaachen.de](mailto:sboesveld@ukaachen.de), [v.heine@biotec.rwth-aachen.de](mailto:v.heine@biotec.rwth-aachen.de),  
[jans@dwz.rwth-aachen.de](mailto:jans@dwz.rwth-aachen.de)

*Clostridium difficile* is a spore-forming bacterium which constitutes a major health threat due to the production of two secreted toxins, TcdA and TcdB. These toxins bind to cell-surface glycans and destroy intestinal epithelial cells thereby leading to pseudomembranous colitis. In many cases, the disease results in death of the patient [1]. To prevent that from happening, our project aims to scavenge the toxins via glycan-functionalized microgels before they can enter the epithelial cells. Currently, the Galili-epitope, a trisaccharide, containing galactose (Gal) and *N*-acetylglucosamine (GlcNAc), appears as one of the best characterized, however, non-human glycan ligand for TcdA. [R.M. Cherian et al., 2016]. Recent studies identified human milk oligosaccharides as potential binders of TcdA and TcdB [A. El-Hawiet et al., 2015, T. T. H. Nguyen et al., 2016]. To screen for high affinity glycan ligands, multivalent presentation is crucial [Laaf et al., 2017]. We have already demonstrated high affinity binding of the TcdA receptor domain on Galili-modified glycopolymer brushes [R. R. Rosencrantz et al., 2016] as well as selective binding of lectins in glycan-functionalized microgels [Jans et al., 2017]. In the present project we synthesize a multivalent glycan ligand library presented on microgels and neo-glycoproteins [Laaf et al., 2017]. We investigate the scavenging efficacy of the microgels by an assay measuring TcdA-mediated cell death. Furthermore, we established a mouse model of *Clostridium difficile* infection monitoring toxin concentrations before and after microgel treatment. During the acute phase, we observed up to 1.5 µg TcdA and TcdB per gram stool, respectively. In conclusion, we have established in vivo and in vitro models of *Clostridium difficile* infection and are pursuing several promising strategies, by screening of a ligand library and glycan-functionalized microgels, to efficiently scavenge bacterial toxins.

### 33) Electrochemical deposition of polyelectrolytes

**Sabine Schneider**

*Physical Chemistry II at the RWTH Aachen*

[sabine.schneider@pc.rwth-aachen.de](mailto:sabine.schneider@pc.rwth-aachen.de)

Introduction of charges into polymers leads to a possible interaction of the resulting polyelectrolyte with oppositely charged counterions based on electrostatic attraction (host-guest interplay). In case of redox-active counterions, the charge of these guest molecules can be changed by electrochemical means [1]. At the same time, the solubility of this complex is changed at the electrode, leading under certain circumstances to an electrochemically-induced film formation. Hence, we address cationic polymers made of quaternized poly(dimethylaminoethyl methacrylate) and its derivatives. We study the influence of polymer architecture and composition on the polyelectrolyte electrodeposition onto platinum with help of hexacyanoferrates. Hydrodynamic voltammetry using a rotating ring disk electrode (RRDE) is a powerful method to learn about the interactions of polymers and electroactive species [2,3]. In addition, the RRDE allows a quantification of the deposition efficiency DE in dependence of polyelectrolyte molar mass, architecture[4] and composition[5]. The DE assigns the ratio of current which was used to produce the deposited electroactive species compared to the total current. Hence, linear polymers, star-shaped polymers and microgels are investigated. Then, the RRDE results demonstrate that linear polymers of moderate molar mass are most efficient in the deposition due to pronounced intermolecular physical crosslinking (by help of the hexacyanoferrates), while branching and higher molar mass favors more intramolecular crosslinking, which can even prevent deposition [2-4]. Further changing the polymer structure, the DE is reduced by replacing the ester linkages with more hydrophilic amide bonds, by replacing the methacrylates with a more hydrophilic acrylates or by introducing primary ammonium groups instead of quaternary ammonium groups[5]. Finally, the combination with an electrochemical quartz crystal microbalance (EQCM) reveals different water contents in these films.

[1] Plamper, F. A.: *Adv. Polym. Sci.* 2015, 266, 125.

[2] Mergel, O., Gelissen, A. P. H., Wünnemann, P., Böker, A., Simon, U., Plamper, F. A.: *J. Phys. Chem. C* 2014, 118, 26199.

[3] Mergel, O., Wünnemann, P., Simon, U., Böker, A., Plamper, F. A.: *Chem. Mater.* 2015, 27, 7306.

[4] Mergel, O.; Kühn, P. T.; Schneider, S.; Simon, U.; Plamper, F. A., *Electrochimica Acta* 2017, 232, 98–105.

[5] Schneider, S.; Janssen, C.; Klindtworth, E.; Mergel, O.; Möller, M.; Plamper, F. A., *Polymers* 2018, 10, 429.

## 34) When microgels meet membranes

**Michael Kather**

*Chemical Process Engineering at the RWTH Aachen*

[michael.kather@avt.rwth-aachen.de](mailto:michael.kather@avt.rwth-aachen.de)

For a long time microgels have been used for medical applications like drug delivery systems or antibacterial agents, but also as sensors, catalysts and even fertilizers. We want to shed light on a new field of use for microgels, namely membranes. By combining microgels with membranes, one can create thermo-responsive membranes with tunable selectivity and permeability. Furthermore, the ion selectivity of the membrane can be tuned using charged copolymer microgels. Microgel coated membranes do not only find application in filtration processes, but can also be used for tissue engineering, allowing the growth of cells on the microgel surface.

## 35) In silico modelling of microgels at interfaces

Fabrizio Camerin

*Complex Systems at the Sapienza University of Rome*

[fabrizio.camerin@uniroma1.it](mailto:fabrizio.camerin@uniroma1.it)

Manifold experimental studies have recently pointed out how stimuli-sensitive microgels can provide a unique approach to emulsions [1]. Their stability, in fact, can be easily controlled trading on the temperature and the pH of the solutions, being the responsiveness to these parameters one of the features for which microgels are widely employed in various fields. In contrast to rigid particles that stabilize Pickering emulsions solely via interfacial tension effects, a comprehensive understanding of soft emulsion stabilizers cannot lack of a description in terms of the microgel swelling, elasticity and deformability [2]. We are now able to provide novel theoretical insights in this respect, thanks to a cutting-edge model that reproduces in silico the polymeric network of PNIPAM microgels [3]. After having tested the response of this microgel model to a coarse-grained explicit solvent [4], we perform Molecular Dynamics simulations of the liquid-liquid interface. In contrast to cases where soft ligands are anchored to a hard core, we observe the flattening of the microgel and the spread of the polymer chains at the interface. By varying the parameters of the monomer-solvent potential, we are able to selectively tune the surface tension enabling the asymmetric squeeze of the network, as expected for solvents of different qualities. Moreover, we note a dependence on the number of crosslinks of the microgel: the higher their amount, the stiffer the polymer network. The newly designed setup will allow us to provide a three-dimensional characterization of the microgel positioning and microstructure at the interface, paving the way to the calculation of multiple particles' effective interactions.

[1] W. Richtering *Langmuir* 2012, 28, 17218–17229.

[2] L. Isa et al., *Phys. Chem. Chem. Phys.*, 2017, 19, 8671.

[3] N. Gnan, L. Rovigatti, M. Bergman, E. Zaccarelli, *Macromolecules* 50 (21), 2017.

[4] F. Camerin, N. Gnan, L. Rovigatti, E. Zaccarelli, In preparation.

We acknowledge support from ERC Consolidator Grant 681597 MIMIC

## 36) Microfluidic $\mu$ -gel filtration monitored by 4-electrode impedance spectroscopy

**Arne Cinar**

*Chemical Process Engineering at the RWTH Aachen*

[arne.cinar@avt.rwth-aachen.de](mailto:arne.cinar@avt.rwth-aachen.de)

A promising technology for concentrating microgels after synthesis is membrane filtration. The continuous and easy up-scalable process shows good results in macroscopic experiments but is limited by severe reversible and irreversible fouling. For solving this limitation and optimizing the process a better understanding of the interaction of microgels with themselves and on surfaces is necessary. Therefore, we developed a microfluidic cross flow filtration device to grow and monitor a microgel fouling layer on a membrane. The chip including a porous membrane with pore sizes about 1 micron is produced by PDMS replica molding. The casting mold is a multi-photon lithographical printed structure closing the gap between microscale fluidics and mesoscale measurement techniques. The fouling behavior is monitored with a four electrode impedance spectroscopy serving as reliable and accurate measurement in a wide frequency range. Additionally, visual and fluorescent observation of the cake layer gives detailed information about the fouling layer formation and the interaction of microgels with themselves.

## 37) Dynamics of the cononsolvency of poly-*N*-isopropylacrylamide microgels in water-methanol mixtures

**Katja Nothdurft**

*Physical Chemistry II at the RWTH Aachen*

[nothdurft@pc.rwth-aachen.de](mailto:nothdurft@pc.rwth-aachen.de)

Crosslinked poly-*N*-isopropylacrylamide (pNIPAM) is swollen in both water and methanol (MeOH). However, a drastic volume loss is observed upon changing the solvent ratio of water/MeOH to a specific composition (0.17 – 0.4 mol% MeOH). This effect is referred to as cononsolvency. Cononsolvency couples the volume phase transition to the transport of the cosolvent into the polymeric network. Hence, the mechanism is fundamentally different from the temperature-dependent collapse. So far, the mechanisms underlying cononsolvency have not been fully elucidated. In this work, we focus on the dynamics of the cononsolvency of pNIPAM microgels. To this end, pNIPAM microgels were synthesized by microfluidics. The dynamic behavior during a solvent jump from water to a 20 mol% MeOH/water mixture was investigated in a microfluidic observation channel by Confocal Raman Spectroscopy. Here, the composition of the continuously changing solvent mixture was quantified within the polymer network and in the channel next to the gel by spectral analysis using indirect hard modeling. The results were compared to the size evolution of fluorescent microgels observed in identical experiments using Confocal Fluorescence Microscopy. The experimental data provide unique detailed insight into the volume phase transition due to cononsolvency.

## **38) Behavior of Microgel at different environments**

**Boyang Zhou**

*Soft Condensed Matter at the Georgia Institute of Technology*

[bzhou71@gatech.edu](mailto:bzhou71@gatech.edu)

Microgel, from its name, we know that it is small and behave like a gel, which will change its shape at different environments. The poster will present the size characterization of microgel at different temperature and pH. Also, the poster will include data taken from Neutron Spin Echo experiment.



## 39) Responsive microgels adsorbed at solid interfaces – inner structure information and mechanical properties by AFM

**Friederike Schulte**

*Physical Chemistry II at the RWTH Aachen*

[friederike.schulte@rwth-aachen.de](mailto:friederike.schulte@rwth-aachen.de)

Microgels are highly interfacial active, although not being amphiphilic. They readily adsorb to liquid/liquid, liquid/air or solid interfaces and deform. Their interfacial behavior makes microgels useful for many applications in the field of advanced polymeric coatings. Not only the temperature-induced changes in topography but also of the mechanical properties of the microgels play an important role, e.g. for cell adhesion on a microgel coated surface. We studied microgels with unique internal structures, (i) one with a rigid silica core and a PNIPAM shell, (ii) hollow microgels obtained by dissolving the silica core, and (iii) ultra-low cross-linked microgels. The morphology and nanomechanical properties of these microgels at surfaces were investigated with an atomic force microscope (AFM). An important parameter is the size of the probe compared to the dimensions of the microgel. We will demonstrate that indentation experiments using a sharp tip lead to penetration of the porous swollen microgel networks. Therefore, force-distance curve measurements enable to probe the segment density distribution orthogonal to the substrate of adsorbed single microgels. Measurements using blunt tips are causing a compression of the microgel and provide information on their global mechanical properties.

## 40) Degradable microgels by radical ring opening polymerization (RROP)

Larissa Hussmann

*Biotechnology at the RWTH Aachen*

[hussmann@dwi.rwth-aachen.de](mailto:hussmann@dwi.rwth-aachen.de)

Microgels have been applied in tissue engineering, release systems and coating devices as they contain a porous structure, are able to swell in water and absorb water. Especially Poly(*N*-vinylcaprolactam) (PVCL) microgels are interesting candidates for application in biomaterials due to their biocompatibility. In order to provide degradable units in the polymer backbone to support a drug-release system, our work is focused on the incorporation of a cyclic ketene acetal. Thus after radical ring opening polymerization (RROP) a degradable ester function is provided [1]. Due to their degradability as well as ability to solubilize hydrophobic molecules, the received microgels may be used in a broad range of bio-medical applications [2]. Also by varying the copolymer structure of microgel chains, it is expected to control the volume phase transition temperature (VPTT) and swelling of the microgels in aqueous solutions. Furthermore, modifications such as the synthesis of core-shell particles or two-step degradation systems using a degradable crosslinker will be then approached.

[1] Bailey, W.J., Z. Ni, and S.-R. Wu, *Journal of Polymer Science: Polymer Chemistry Edition*, 1982. 20(11): p. 3021-3030.

[2] Shi, Y. and S. Agarwal, *e-Polymers*. 2015. p. 217.

## 41) Continuous precipitation polymerization of microgels

**Hanna Wolff**

*Chemical Process Engineering at the RWTH Aachen*

[hanna.wolff@avt.rwth-aachen.de](mailto:hanna.wolff@avt.rwth-aachen.de)

Microgels are commonly synthesized in batch experiments yielding quantities sufficient to perform characterization experiments to study their physical properties. While microgels develop more application potential, little attention is yet paid to the question whether (a) they can be produced continuously on a larger scale, (b) whether synthetic routes can be easily transferred from batch to continuous synthesis and (c) their properties can be precisely controlled as a function of synthesis parameters under continuous flow reaction conditions. We present a new continuous synthesis process of two typical but different microgel systems and compare in depth their size, size distribution and temperature responsive behavior to microgels synthesized using batch process.

## 42) The effect of concentration of microgels suspensions on the shape transformation of microgels

**Andrey Rudov**

*DWI – Leibniz Institute for Interactive Materials*

[rudovaa@gmail.com](mailto:rudovaa@gmail.com)

The macroscopic behavior of microgel suspensions is predicated on the properties and primary structure of the single microgels. As opposed to the hard particles, the microgels are soft colloids and can readily change both their shape and their volume under an applied stress. These fundamental features affect significantly their phase behavior and the macroscopic rheological response of a microgel suspension. For example, when microgel particles are driven to high packing concentrations, they start to deform and, thus, it is possible to keep concentrating of the system up to volume fractions of 1. Further concentration will induce the de-swelling of the microgel particles due to steric repulsion with other particles and raise volume fractions even higher than 1. For comparison, the maximum packing fraction for hard spheres (if crystallization is allowed) is equal to 0.74, which corresponds to a FCC or HCP arrangement. The presence of the fuzzy shell has an effect on the crystalline phase formed by microgels in suspension (metastable BCC structure or coexistence of face centered cubic (FCC)-hexagonal close packed (HCP) were found in concentrated suspensions of PNIPAM microgels). In the last years many advances have been achieved in the design of microgels with different architecture. In addition to the usual thermo-responsive particles that can be described as fuzzy spheres, core-shell with a rigid core and hollow shell microgels have been successfully synthesized. They represent a new kind of system that can show distinguishable and unexplored properties with respect to colloidal suspensions. The hollow microgels are of particular interest. The presence of the cavity could induce either self-similar de-swelling of hollow microgel or its deformation and anisotropic collapse upon concentration of suspension. In the second case anisotropy in the entire suspension is expected to occur. In this work we have presented perhaps the first detailed experimental and theoretical (computer simulation) description of response of continuous and hollow microgels to the increase of particle concentration in suspension. We have compared the behavior of three alike systems: suspension of continuous microgels, suspension of continuous microgels with small fraction of hollow microgels and suspension of hollow microgels. We characterized our systems directly at the single-particle level. We investigate morphology of the microgels: their sizes, density profiles, inertia tensor, and relative shape anisotropy. Besides that, we have focused on the description of the arrangement of the particles and symmetry in the suspensions in the high-concentration regimes.

## 43) Constraints for set-membership parameter estimation

**Falco Jung**

*Process Systems Engineering at the RWTH Aachen*

[falco.jung@avt.rwth-aachen.de](mailto:falco.jung@avt.rwth-aachen.de)

This contribution analyzes formulations for the constraints of a feasible set of an optimization-based parameter identifiability analysis. For model discrimination and experimental design, parameter estimation and identifiability play a key role. In particular, it is desirable to determine the feasible parameter set, i.e., parameters for which the model outputs remain within defined bounds of available measurements. To improve the numerical tractability of the problem, the feasible set can be over-approximated by a box. Formulations for the constraints of the feasible set are in the focus of this contribution. In guaranteed parameter estimation the set is bounded by a predefined absolute or relative error of single measurement points. Alternatively, the feasible region can be defined by a statistical analysis of the model deviation from all available measurements. The formulations are applied to a case study with a nonlinear model of a complex microgel synthesis reaction. Finally, the approximations of the feasible region are compared to the confidence ellipsoid predicted with an established method for parameter identifiability, which is based on linearization of the model.