QLUSTER
Quantum and Classical Ultrasoft Matter

Dear Reader,

This second year was a very active year, during which most of the foreseen technical and soft skill courses foreseen in the project plans were given. Students gathered at the locations of various consortium partners to follow those courses, enjoy other activities and discuss life as a QLUSTER student.

Early 2024 we had our first yearly meeting in Ljubljana, during which all students presented their projects. We are now in the process of preparing the second yearly meeting, which will be held in San Sebastián, and hope we will manage to make it as productive as the first meeting.

Best Regards,

Team QLUSTER

QLUSTER training activities

This second year of our project was packed with training activities, the students traveled to five different countries to attend the various courses organized by the consortium. Moreover, the planned QLUSTER summer school took place at the Enrico Fermi International School of Physics in July 2024.

The year started off with our consortium meeting year 1 in Ljubljana, Slovenia, on February 13 2024. We all met up and each student presented their part of the project to the Project Officer who tuned in online.

The Advanced Training Module T1 on *Advanced Concepts in Soft Matter* and Transferrable Skills course S1 on *Scientific Data Presentation and Visualization* were also imparted in Ljubljana in the days after the consortium meeting. S1 focused on poster design and how clearly present scientific data.

The second series of training course took place in Heraklion, Crete, on April 15-17 2024. The Transferable Skills Course S2 on *Communication and Writing Skills* was organized so as to provide the participants with an insight into the way a presentation and a research paper are structured, what key points to consider, tips for a comprehensive presentation

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or well received paper, tips on how to address specific audience, how to focus on the punchline of the work. The Advanced Training Module T2 on *Experimental Methods in Soft Matter* was organized so as to provide the participants with the basic properties of soft materials and the experimental methods and protocols used to probe them.

QLUSTER Summer School on *Topology and Materials*, took place July 17-22 (2024) at the Villa Monastero in Varenna, Italy. It was attended by all 9 QLUSTER students and 39 other international students. There were 12 lecturers giving lectures on topics such as topological geometry, topological polymers, knots and links in physics and biology, topological defects in liquid crystals, topological colloids, quantum numbers, insulators, quantum chemistry, etc.

Third QLUSTER training course T5 on *Structure and dynamics in systems with ultrasoft interactions* was organized in Rome in the week after the school. It focused on fundamental concepts of slow dynamics in soft matter systems, focusing in the glass and gel transitions and in polymer dynamics.

The Fourth and last QLUSTER training series took place in Innsbruck. The Soft Skills Course S3 on *Ethics and Gender Aspects*, Training course T3 on *Quantum Matter* and Training course T4 on *Computational Methods* were given that week. The students also attended one day of the IOQOI conference (International Conference on Quantum Optics and Quantum Information), taking place in Innsbruck the same week.

We are happy to announce that the CECAM workshop *Charged Soft Matter: Bridging Theory and Experiments*, which is co-organized by QLUSTER's members of the University of Vienna, has recently been approved. The workshop will take place at the CECAM node in Vienna in September 2025 and will be a key training event for QLUSTER's students. The workshop will discuss topics such as coacervation, supramolecular assembly, transport, function or responsiveness in charged soft matter systems (colloids, proteins, viruses, polyelectrolytes, polypeptides, etc).

Scientific highlights

This second year there were multiple papers that came out within the context of the QLUSTER project. Three of those are highlighted here; for more, check out our webpage as specified below.

Effects of Linking Topology on the Shear Response of Connected Ring Polymers: Catenanes and Bonded Rings Flow Differently

Farimani, Reyhaneh A.; Dehaghani, Zahra Ahmadian; Likos, Christos N.; Ejtehadi, Mohammad Reza, Physical Review Letters **132**: 148101 (2024).

We performed computer simulations to investigate mechanically linked (poly[2]catenanes) and chemically bonded (bonded rings) pairs of self-avoiding ring polymers in steady shear. The bonded rings develop a novel motif, termed gradient tumbling, rotating around the gradient axis. For the poly[2]catenanes the rings are stretched and display another new pattern, termed slip tumbling. The dynamics of bonded rings is continuous and oscillatory, whereas that of (poly[2]catenanes) is intermittent between slip-tumbling attempts. These findings demonstrate the interplay between topology and hydrodynamics in dilute solutions of connected polymers.

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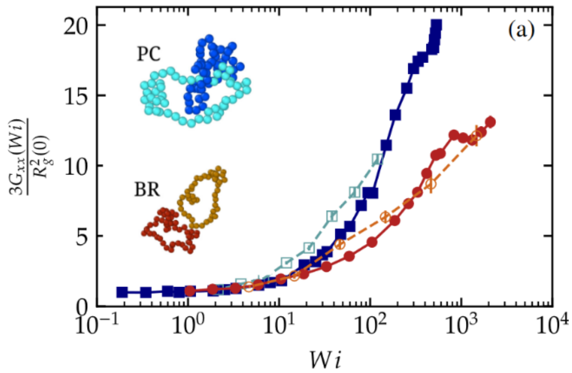


Time averages of the normalized flow-direction component of the gyration tensor of the poly[2]catenane (PC) and the bonded rings (BR) system (entire molecules) in shear flow, as a function of the Weissenberg number. The dark blue-filled squares refer to the PC (with hydrodynamic interactions: +HI), red-filled circles to BR (+HI), empty sky blue squares to PC (without hydrodynamic interactions: −HI), and empty orange circles to BR (−HI). The simulation snapshots show a PC molecule and a BR molecule at equilibrium (zero Weissenberg number).

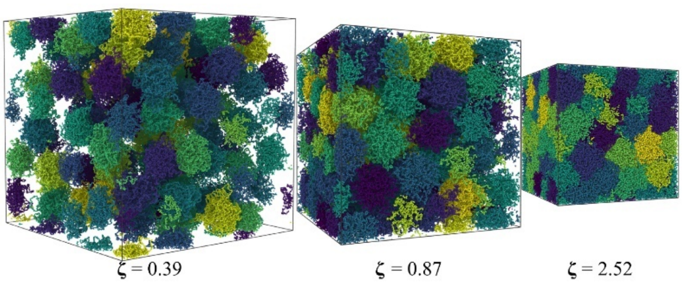
Numerical Study of Neutral and Charged Microgel Suspensions: From Single-Particle to Collective Behavior,

Giovanni Del Monte and Emanuela Zaccarelli, Physical Review X **14**, 041067 (2024).

Understanding the transition to a glassy state of matter is one of the most challenging problems in condensed matter physics. In recent years, soft colloids have emerged as favorite model systems to tackle this problem. When the colloidal particles contact their neighbors, they can shrink, deform, or interpenetrate, allowing researchers to explore states at the very high densities necessary for glass transition studies. Readily accessible in experiments, such high-density states are hard to simulate due to the complex internal structure of the particles. Here, we perform the first numerical study of many microgels—prototypes of soft colloids—with a realistic structure that also contains charged groups as in experiments.

We explore a wide variety of dense states and characterize the suspension with single-particle resolution, quantifying the sequence of mechanisms coming into play and finding quantitative agreement with recent superresolution microscopy experiments. We also monitor the suspension as a whole and find evidence of nonmonotonicity of structural correlations upon increasing packing fraction that is not accompanied by a similar feature in the dynamics, finding deviations from simple coarse-grained elastic models. This is again in agreement with experimental evidence.

The successful description of experimental observations makes our study the first step toward a microscopic understanding of soft-particle suspensions under ultradense conditions.



Representative snapshots of neutral microgel suspensions at packing fractions ζ=0.39, 0.87, and 2.52, from left to right, respectively. Box dimensions are reproduced with the right proportions so that deswelling of the microgels can be visualized.

Time-reversal in a dipolar quantum many-body spin system,

Sebastian Geier, Adrian Braemer, Eduard Braun, Maximilian Müllenbach, Titus Franz, Martin Gärttner, Gerhard Zürn, and Matthias Weidemüller, Physical Review Research **6**, 033197 (2024).

Time reversal in a macroscopic system contradicts daily experience. It is practically impossible to restore a shattered cup to its original state by just time reversing the microscopic dynamics that led to its breakage. Yet, with the precise control capabilities provided by modern quantum technology, the unitary evolution of a quantum system can be reversed in time. Here, we implement a time-reversal protocol in a dipolar interacting, isolated many-body spin system represented by Rydberg states in an atomic gas. By changing the states encoding the spin, we flip the sign of the

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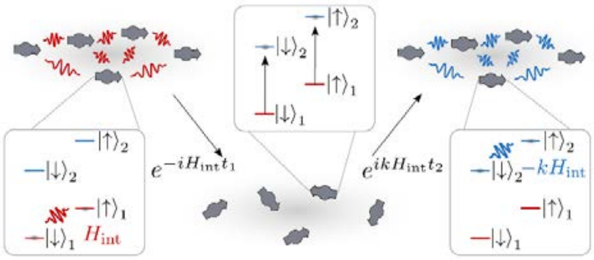
interaction Hamiltonian, and demonstrate the reversal of the relaxation dynamics of the magnetization by letting a demagnetized many-body state evolve back in time into a magnetized state. We elucidate the role of atomic motion using the concept of a Loschmidt echo. Finally, by combining the approach with Floquet engineering, we demonstrate time reversal for a large family of spin models with different symmetries. Our method of state transfer is applicable across a wide range of quantum simulation platforms and has applications far beyond quantum many-body physics, reaching from quantum-enhanced sensing to quantum information scrambling.



Time reversal on a Rydberg quantum many-body system; sketch of the protocol. The time reversal is based on transferring the state between two spin-1/2 encodings in the Rydberg manifold.

All QLUSTER's publications can be found on the website of Digital CSIC dedicated to the project: https://digital.csic.es/cris/project/pj00278

All news on activities can be found on our News page: https://www.qluster-horizon.eu/blog

You're always welcome to send us an email at qluster.project@gmail.com

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