DEPARTMENT OF SOLID STATE PHYSICS F-5

Our research programme focuses on studying the structure and dynamics of disordered and partially ordered condensed matter at the atomic and molecular levels, with a special emphasis on phase transitions. The purpose of these investigations is to discover the basic laws of physics governing the behaviour of these systems, which represent the link between perfectly ordered crystals, on the one hand, and amorphous matter, soft condensed matter and living systems, on the other. Such knowledge provides the key to our understanding of the macroscopic properties of these systems and is an important condition for the discovery and development of novel multifunctional materials, nanomaterials and biomaterials for new applications. An important part of the research programme is devoted to the development of new experimental methods and techniques in the field of magnetic resonance and magnetic resonance imaging, optical microscopy and imaging, scanning tunnelling, electronic and atomic force microscopy, as well as cold atoms and quantum technologies.

Head:
Prof. Igor Muševič

The research programme of the Department of Solid State Physics at the Jozef Stefan Institute is performed in close collaboration with the Department of Physics at the Faculty of Mathematics and Physics of the University of Ljubljana, the Institute of Mathematics, Physics and Mechanics and the Jožef Stefan International Postgraduate School. In 2021 the research was performed within three research programmes:

- Magnetic resonance and the dielectric spectroscopy of smart new materials
- Physics of Soft Matter, Surfaces and Nanostructures
- Experimental Biophysics of Complex Systems

I. Research Programme: Magnetic Resonance and Dielectric Spectroscopy of Smart New Materials

The research of the programme group *Magnetic Resonance and Dielectric Spectroscopy of Smart New Materials* in 2021 was focused on the study of physical phenomena in condensed matter at the atomic and molecular levels. The main goal of our investigations was to discover the basic laws of physics governing the behavior of the investigated systems, from the atomic to the macroscopic levels. The attained knowledge provides a key to the understanding of the microscopic and macroscopic properties of various types of solids and is an important condition for the discovery and development of new multifunctional materials and nanomaterials for novel technological applications.

We studied enigmatic excitations in quantum spin liquids, peculiar spin dynamics in bulk topological skyrmion lattices, investigated the electrical, magnetic and thermal properties of high-entropy alloys, used shear flow to control the shape memory of polymer-resin-dispersed liquid-crystal elastomer microparticles, and topological and caloric effects in multiferroics and soft-matter for green-energy applications and finally fullerene radical spins as qubits. Moreover, we continued to develop novel methods based on experiments with cold atoms.

In our research we used the following complementary experimental techniques:

- Nuclear magnetic resonance (NMR), electron paramagnetic resonance (EPR) and nuclear quadrupole resonance (NQR),
- Nuclear double resonance ^{17}O–H and ^{14}N–H,
- Fast field cycling NMR relaxometry,
- Linear and non-linear dielectric spectroscopy in the range 10^{-2} Hz to 10^{9} Hz,
- Frequency-dependent ac calorimetry,
- Measurement of electrical and thermal transport coefficients,
- Magnetic measurements,
- Methods involving ultra-cold atoms.

The research programme was performed in close collaboration with the Department of Physics at the Faculty of Mathematics and Physics of the University of Ljubljana, the Institute of Mathematics, Physics and Mechanics, and the Jožef Stefan International Postgraduate School, as well as many recognized research groups from world-leading institutions.

In 2021 the members of the programme group published 65 original scientific papers in international peer-reviewed scientific journals and one review article. Among these, we single out an article published in *Nature Physics* (IF = 20), an article published in *Angewandte Chemie, Intl. Ed.* (IF = 15.3), an article in *Nanoscale* (IF = 7.8) and several articles in *Physical Review B* (IF = 4).

Our reasearh was directed to the following topics: quantum and topological magnetism, high-entropy alloys, functional materials, and cold atoms. Our main results are as follows:

1. Quantum and topological magnetism

Tina Arh, **Matjaž Gomilšek**, **Primož Koželj**, **Stane Vrtnik**, and **Andrej Zorko**, together with collaborators from China and Croatia, discovered magnetic ordering in the compound $Y_3Cu_9(OH)_{18}[Cl_8(OH)]$. This compound is an antiferromagnet on the distorted kagome spin lattice, which was previously believed to be magnetically disordered. However, complementary measurements of the bulk magnetization, specific heat, and magnetic torque revealed a Néel transition at 11 K. The study of high-quality crystals using optimized hydrothermal synthesis was crucial for the discovery. This suggests that the absence of the magnetic ordering in lower-quality samples is of extrinsic origin. The work was published in a paper by W. Sun et al., "Magnetic ordering of the distorted kagome antiferromagnet $Y_3Cu_9(OH)_{18}[Cl_8(OH)]$ prepared via optimal synthesis", *Phys. Rev. Mater.* **5**, 064401 (2021).

Matjaž Gomilšek, **Tina Arh**, and **Andrej Zorko**, together with a colleague from the Department of Theoretical Physics, studied the temperature dependence of dynamic spin correlations of a kagome lattice antiferromagnet. They found that even in the purely isotropic case of Heisenberg exchange interactions between nearest neighbours, chiral spin fluctuations dominate at low energies, which leads to an enhanced low-frequency response at the M point of the extended Brillouin zone. The inclusion of Dzyaloshinskii-Moriya (DM) type magnetic anisotropy leads to an anisotropic dynamic response and magnetic ordering. These theoretical predictions agree very well with measurements of inelastic neutron scattering and nuclear spin-lattice relaxation on the paradigmatic kagome antiferromagnet herbertsmithite, where the effect of DM anisotropy is small, as well as with the results of nuclear spin-lattice relaxation on the new representative of the kagome antiferromagnet $YCu_3(OH)_6Cl_3$, where, however, the effect of magnetic anisotropy is much stronger. They presented their findings in the article by P. Prelovšek *et al.*, "Dynamical spin correlations of the kagome antiferromagnet", *Phys. Rev. B* **103**, 014431 (2021).

Tina Arh and **Andrej Zorko**, together with colleagues from India and Switzerland, studied the magnetic properties of the two-dimensional spin lattice Ba_2MnTeO_6. Using complementary measurements of muon spectroscopy, magnetization and specific heat, they showed that the substance orders magnetically at a temperature of T_N = 20 K. They found that strong spin correlations are established well above the temperature of magnetic ordering, while spin dynamics remain present even in the magnetically ordered phase. Theoretical calculations have shown that this is due to the strong frustration of exchange interactions in and between the planes. They presented their findings in an article by J. Khatua *et al.*, "Development of short and long-range magnetic order in the double perovskite based frustrated triangular lattice antiferromagnet Ba_2MnTeO_6", *Sci. Rep.* **11**, 6959 (2021).

Andrej Zorko, together with colleagues from India, the USA, France, and Germany, studied the magnetic ordering of the triangular Heisenberg antiferromagnet α-$HCrO_2$ with a wide range of experimental and theoretical techniques. Despite the magnetic ordering at a Néel temperature of T_N = 22.5 K, a wide temperature range with very slow spin fluctuations was detected in the magnetically controlled phase. Since similar behaviour has previously been observed in the structurally related compounds $NaCrO_2$ and α-$KCrO_2$, such an unusual response is apparently a general characteristic of triangular antiferromagnets with ABC stacking. The results of this research were published in the article by K. Somesh *et al.*, "Universal fluctuating regime in triangular chromate antiferromagnets", *Phys. Rev. B* **104**, 104422 (2021).

Matej Pregelj, **Andrej Zorko**, and **Denis Arčon**, together with colleagues from Croatia and Switzerland, studied the dielectric response of the compound b-$TeVO_4$. They discovered a ferroelectric response of the vector-chiral magnetic ground state, where the magnitude of electrical polarization is proportional to the intensity of the magnetic reflections in neutron scattering. This suggests that the inverse Dzyaloshinskii-Moriya mechanism is responsible for the coupling between electrical polarization and magnetic order. Linear magnetoelectric coupling was not detected, but a very strong dependence of the electric coercive field on an external magnetic field was discovered, which opens the possibility of controlling recorded magnetoelectric information. They presented their findings in the article M. Dragičević *et al.*, "Control of a polar order via magnetic field in a vector-chiral magnet", *Phys. Rev. B* **104**, L121107 (2021).

Matjaž Gomilšek, in collaboration with partners from the United Kingdom and the USA, studied staggered molecular spin chains $[pym–Cu(NO_3)_2(H_2O)_2]$ (Cu-PM; pym = $C_4H_4N_2$) and $[Cu(pym)(H_2O)_4]SiF_6 \cdot H_2O$ (Cu-SiF). Cu-PM is one of only a few systems with a field-induced gapped phase described by sine-Gordon (SG) quantum field theory with soliton, anti-soliton, and bound-state excitations. Using muon spectroscopy (μSR), supported by density functional theory (DFT) calculations, they discovered a transition from the SG regime to long-range order in Cu-PM at temperatures below T_N = 0.23(1) K and studied the resulting magnetic moments. No such transition was found in the chiral Cu-SiF. At temperatures above the SG spin gap both systems enter a perturbative regime with fractional spinon excitations. Using μSR the authors demonstrate that spin transport in this regime is ballistic in Cu-PM and diffusive in Cu-SiF, demonstrating the crucial impact of anisotropic perturbations on spin transport in quantum spin chains. The work was published in the paper B. M. Huddart *et al.*, "Magnetic order and ballistic spin transport in a sine-Gordon spin chain", *Phys. Rev. B* **103**, L060405 (2021).

Matjaž Gomilšek, in collaboration with partners from the United Kingdom, studied peculiar spin dynamics in the bulk topological skyrmion lattice (SkL) systems Cu_2OSeO_3 and $Co_xZn_yMn_{20-x-y}$. Using muon spectroscopy (μSR) they found that Cu_2OSeO_3 exhibits emergent dynamic behaviour at MHz frequencies, likely due to collective SkL excitations. Complementing μSR with density functional theory (DFT) and dipolar field calculations they further demonstrated that a separate, metastable SkL phase in Cu_2OSeO_3 is unlikely to be a bulk phase and may instead be found at sample boundaries and surfaces. In $Co_8Zn_9Mn_3$ the authors observe ~2 GHz excitations that reduce in frequency near the T_c of the SkL phase under various applied fields (contrasting this with thin plate results implies strong confinement effects in the latter), while in $Co_8Zn_8Mn_4$ similar behaviour is observed over a much wider range of temperatures, implying that this kind of spin dynamics persists beyond the SkL phase, raising the question of its ultimate origin. The work was published in the paper T. J. Hicken *et al.*, "Megahertz dynamics in skyrmion systems probed with muon-spin relaxation", *Phys. Rev. B* **103**, 024428 (2021).

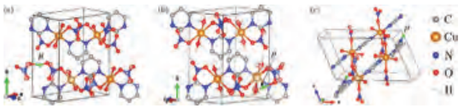

Figure 1: Low-energy muon sites in Cu-PM identified via DFT calculations.

Matjaž Gomilšek, in collaboration with partners from the United Kingdom, studied the spin dynamics in the exotic topological spin texture materials MnNiGa and $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$. Namely, in thin lamellae, MnNiGa was reported to host biskyrmions (topological charge $N = 2$ excitations, which form as bound pairs of same-chirality $N = 1$ Bloch skyrmions), while $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ was found to host antiskyrmions ($N = -1$ excitations with complex winding around the circumference). Using muon spectroscopy and magnetometry they revealed two spin-reorientation transitions as a function of temperature, with dynamics that slowly reduce in frequency as the upper critical temperature is approached from below. Below the lower transition, persistent spin dynamics over a broad range of frequencies are found to arise continuously in MnNiGa and more abruptly and inhomogeneously in $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$. Unexpectedly, no conclusive dynamical evidence for biskyrmions or antiskyrmions is found in bulk samples, hinting at a possible decisive stabilizing role of confinement effects in thin lamellae samples or exotic dynamics. The work was published in the paper B. N. Wilson *et al.*, "Spin dynamics in bulk MnNiGa and $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ investigated by muon spin relaxation", *Phys. Rev. B* **104**, 134414 (2021).

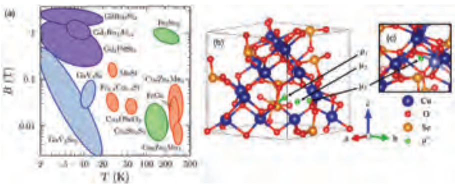

Figure 2: (a) Phase diagram of bulk skyrmion materials. (b,c) Muon sites in Cu_2OSeO_3 identified via DFT.

Martin Klanjšek was invited by the editor of the journal Nature Physics to write a review article in the News & Views section about the progress in elucidating the ground state of the quantum magnet with the kagome lattice. This is an archetypal magnet hosting the exotic quantum spin liquid state, whose exact nature is not yet clarified. The suggested candidate states are all based on spin singlets, but it is not clear whether those are gapped or gapless. Both the recent theoretical works as well as the very recent experiments are divided between the two possibilities. The theories treating structural disorder also predict the possible coexistence of free orphan spins and spin singlets with a varying energy gap. Martin Klanjšek describes his view on the recent surprising discovery of the gradual formation of spin singlets in two quantum magnets with a kagome lattice, which is consistent with theories treating structural disorder. The article was published in M. Klanjšek, "Singlets singled out", *Nature Physics* **17**, 1081 (2021).

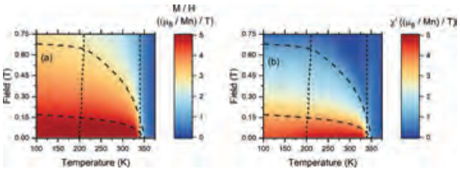

Figure 3: Phase diagram of bulk MnNiGa via (a) DC magnetization and (b) real part of AC susceptibility.

2. High-entropy alloys

In 2021 the research group of the Laboratory for Electrical, Magnetic and Thermal Measurements of Materials (Darja Gačnik, Andreja Jelen, Magdalena Wencka, Jože Luzar, Primož Koželj, Mitja Krnel, Stanislav Vrtnik and Janez Dolinšek) investigated the electrical, magnetic and thermal properties of high-entropy alloys (HEAs), i.e., crystalline solid solutions composed of five or more chemical elements in equi-atomic concentrations.

In the article Spin-glass magnetism of the non-equiatomic CoCrFeMnNi high-entropy alloy, **P. Koželj**, **S. Vrtnik**, **M. Krnel**, **A. Jelen**, **D. Gačnik**, **M. Wencka**, Z. Jagličić, A. Meden, G. Dražić, F. Danoix, J. Ledieu, M. Feuerbacher, **J. Dolinšek**, *J. Magn. Magn. Mater.* **523**, 167579 (2021) we investigated the magnetism of the CoCrFeMnNi HEA with random mixing of the elements on a cubic crystal lattice. We found that the material shows frustrated magnetism of a spin-glass type. We detected the memory effect, where the spin system remembers its cooling history inside the non-ergodic phase. The continuous is stopped for a macroscopic time at a certain temperature, so that the system is isothermally aged. After aging, cooling is resumed to the lowest temperature, where the temperature sweep is reversed and the zero-field-cooled (zfc) magnetization is measured upon heating in a tiny magnetic field. The zfc magnetization then shows a dip at the aging temperature and the magnitude of the dip depends on the aging time. The spin system can remember several consecutive stops at increasingly lower temperatures. The observation of the memory effect in CoCrFeMnNi HEA suggests the use of this material as a thermal memory cell for thermal storing of digital information by pure thermal manipulation, in the absence of a magnetic, electric or electromagnetic field. Figure 4 shows the

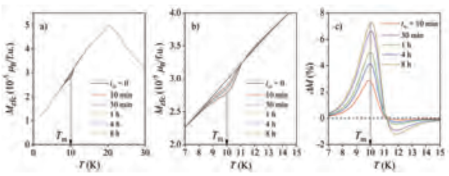

*Figure 4: **(a)** Zfc magnetization M_{zfc} for different aging times t_w = 10 min, 30 min, 1 h, 4 h and 8 h at the aging temperature T_m = 10 K. **(b)** Expanded portion of M_{zfc} in the vicinity of T_m. **(c)** Normalized difference between the reference (unaged) curve M_zfc (t_w=0) and the aged curves, $\Delta M=[M_{zfc}(t_w=0)-M_{zfc}(t_w)]/M_{zfc}(t_w=0)$.*

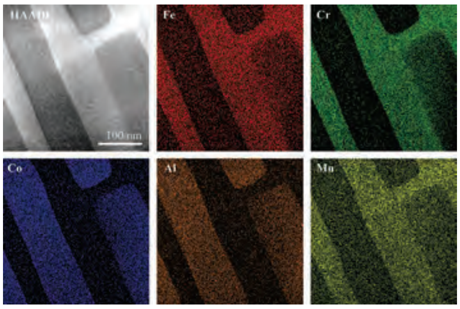

Figure 5: HAADF STEM micrograph and EDS elemental maps of the spinodally decomposed FeCoCrMnAl HEA.

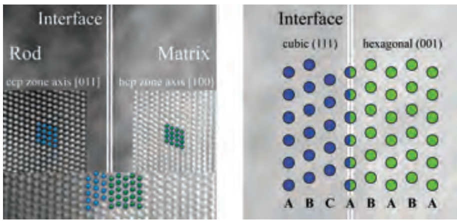

Figure 6: HAADF image of the interface region in the direct space (left panel), showing how the two phases are spatially related. The two insets in the middle show atomic-resolution projection of the ccp precipitate along the [011] zone axis and the hcp matrix along the [100] zone axis. The inset at the bottom shows the atomic structure projection of the interface. Right panel shows schematic representation of the atomic arrangement at the interface. The crystal planes of type (001) of the hexagonal matrix and (111) of the cubic precipitate are parallel to each other and one such plane represents the interface.

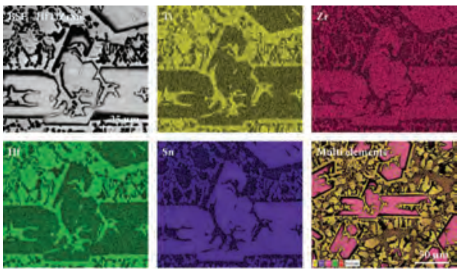

Figure 7: SEM BSE image of the HfTiZrSn HEA (upper-left panel) and EDS elemental maps.

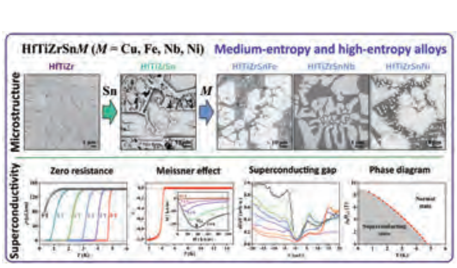

Figure 8: Graphs of microstructure, electrical resistivity at the superconducting transition, Meissner effect, superconducting gap in the electronic density of states at the Fermi energy and the upper critical field as a function of temperature for selected HEAs from the system HfTiZrSnM (M = Cu, Fe, Nb, Ni).

zfc magnetization during heating run, where a dip is observed at 10 K, where isothermal aging upon preceding cooling was performed for times from 10 min to 8 h.

In the paper Collective magnetism of a single-crystalline nanocomposite FeCoCrMnAl high-entropy alloy, A. Jelen, P. Koželj, D. Gačnik, S. Vrtnik, M. Krnel, G. Dražić, M. Wencka, Z. Jagličić, M. Feuerbacher, J. Dolinšek, *J. Alloys Compd*. **864**, 158115 (2021) the group investigated the collective magnetism of the FeCoCrMnAl HEA, which is spinodally decomposed into a two-phase nanocomposite structure of a bcc matrix and B2 (partially ordered bcc) nano-platelets, where each phase has a different chemical composition. Both phases contain 3*d* magnetic transition elements Fe, Co, Cr and Mn, where Fe and Co promote ferromagnetic ordering, while Cr and Mn prefer antiferromagnetic ordering. The resulting magnetism is frustrated, similar to a spin glass. EDS elemental maps of the spinodally decomposed HEA are shown in Figure 5.

In the article Nanostructure and local polymorphism in "ideal-like" rare-earths-based high-entropy alloys, **A. Jelen**, J.H. Jang, J. Oh, H.J. Kim, A. Meden, **S. Vrtnik**, M. Feuerbacher, **J. Dolinšek**, *Mater. Charact*. **172**, 110837 (2021) we reported the polymorphism of rare-earth-based HEAs, which were so far considered as a prototype of an "ideal" single-phase HEA with completely random mixing of the elements on a hexagonal close-packed (hcp) lattice. We have shown that despite the vanishing binary mixing enthalpies of any pair of the employed rare-earth elements (which is a condition for a completely random mixing of the elements in a solid solution), small differences in the atomic radii cause local polymorphism, where the majority matrix is hcp, whereas the elliptical precipitates with a length of several 100 nm have a cubic close-packed (ccp) structure with the same chemical composition. Figure 3 shows the hcp–ccp polymorphism in Y-Gd-Tb-Dy-Ho HEA.

In the paper Structure and Superconductivity of Tin-Containing HfTiZrSnM (M = Cu, Fe, Nb, Ni) Medium-Entropy and High-Entropy Alloys, **D. Gačnik**, **A. Jelen**, **M. Krnel**, **S. Vrtnik**, **J. Luzar**, **P. Koželj**, M. van Midden, E. Zupanič, **M. Wencka**, A. Meden, Q. Hu, S. Guo, **J. Dolinšek**, *Materials* **14**, 3953 (2021) investigated the structure, microstructure, chemical composition and superconductivity in the HEA system HfTiZrSn*M* (*M* = Cu, Fe, Nb, Ni), which contains tin, a so far unexplored element in the context of HEAs. The materials show complicated multi-phase structures. Microstructure and EDS elemental maps of the HfTiZrSn HEA are shown in Figure 7.

Superconductivity was detected in all the HEAs of the HfTiZrSn*M* (*M* = Cu, Fe, Nb, Ni) family, except the one that contains iron (Fe). Figure 8 shows the graphs of microstructure, electrical resistivity at the superconducting transition, Meissner effect, superconducting gap in the electronic density of states at the Fermi energy and the upper critical field as a function of temperature.

3. Functional materials

3.1 Shape memory in polymer dispersed liquid-crystal elastomer microparticles

Saide Umerova, **Matej Bobnar**, **Nikita Derets**, **Boštjan Zalar** and **Andraž Rešetič** in cooperation with Danjela Kuščer (K5) used shear flow to control the shape memory of polymer-resin-dispersed liquid-crystal elastomer microparticles (μLCEs). By taking advantage of the soft elastic nature of polydomain μLCEs, shear stress as a conjugate external field was successfully employed to induce the deformation and mesomorphic ordering of μLCE particles suspended in polydimethylsiloxane (PDMS), rendering them monodomain. Upon cooling from the isotropic phase down to room temperature at a high enough shear, the μLCEs have been shown to assume elongated, long-term stable geometry, exhibiting something resembling shape-memory behaviour. The elongated particles have been found to be aligned along the flow. If this alignment is lost, typically due to mixing, it can be restored using shearing in moderate flows without thermal cycling. If required, the μLCE shape memory can be erased by heating the material to the isotropic phase and then reprogrammed. This could prove to be invaluable in the additive manufacturing of elastic artefacts with a pre-programmed thermomechanical response. The work was published in a paper by S. Umerova, *et al*., Shear flow-controlled shape memory of polymer-resin-dispersed liquid-crystal elastomer microparticles, *Materials & Design* **207** 109836 (2021).

3.2 Topological and caloric effects in multiferroics and soft-matter

We continue studies of the ferroelectric properties, electromechanical and caloric effects, and energy-storage properties in novel multiferroic lead-free materials and soft matter. It was shown that these materials could be utilized in novel technologies of supercapacitors and heat-management devices. We have investigated the Halperin-Lubensky-Ma effect on nematic ordering in liquid crystals and the asymmetric lipid transfer between lipid vesicles. It was demonstrated how nanoparticles of different shapes assemble in the defect lattices of chiral liquid-crystalline phases. B. Rožič was also professionally active in the popularization of science, **B. Rožič** *Ženske, ki spreminjajo obraz znanosti*, Slovenska nacionalna komisija za UNESCO. 2021, p. 50-51 (*Women who are changing the face of science*, Slovenian National Commission for UNESCO). Research has been disseminated in 18 scientific articles in international scientific journals, two chapters, and three invited lectures presented at international scientific meetings. Publications on multiferroics, multicalorics and soft-matter phenomena have recorded more than 600 citations in 2021 (without self-citations).

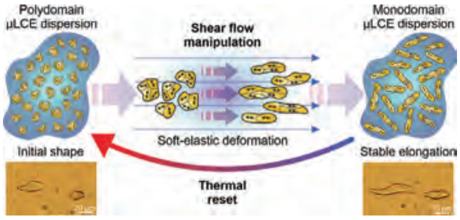

Figure 9: Schematics of shear-driven deformation and temperature 'shape resetting' of µLCEs dispersed in PDMS. The shape relaxation of the µLCEs was observed directly using polarized microscopy.

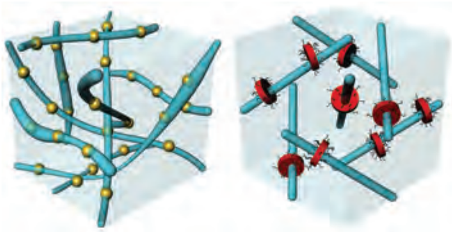

Figure 10: Assembly of spherical nanoparticles in the disclination lines of blue phase III (left panel) and of anisotropic ones in blue phase I (right panel).

3.3. Functional nanostructures

TiO_2 nanostructures doped with Eu^{3+} in Nd^{3+} for temperature sensing

We continued with the investigation of TiO_2 nanostructures doped with lanthanide ions (Eu^{3+} and Nd^{3+}) for temperature measurements at the nanoscale. Lanthanide-based optical nanothermometers are suitable for use in biological applications as they are operating in the physiological temperature range (15 to 50 °C). TiO_2 was used as a support for its low toxicity and biocompatibility. TiO_2 nanoparticles doped with Eu^{3+} and Nd^{3+} ions were prepared using a sol-gel method. XRD, SEM, TEM, XPS and NEXFS techniques were used to determine their physiochemical characteristics. In the case of Eu^{3+} doping, the successful internalization of TiO_2 nanoparticles doped with Eu^{3+} ions in different cells was observed. By measuring the luminescence intensity variation of internalized doped particles, information about the cells temperature variation with a sensitivity of 0.5 K per 1% change of luminosity was obtained. Results were published in **P. Umek** et al., *Nano select* **2**, 1208 (2021) and **P. Umek** et al., *Sensors* **21** 5306 (2021).

Development of a new class of polymer nanocomposites exhibiting more than ten times the enhancement of dipolar response

Dielectric polymers are pervasive in modern electrical systems due to their easy fabrication, high pliability, low dielectric loss, and high dielectric breakdown strength. However, for many electrical applications, their dielectric constant is too low. In collaboration with researchers from Pennsylvania State University we developed a new class of dielectric polymer nanocomposites, where various nanoparticles (0-D fillers) or Fe_2O_3 nanorods and Al_2O_3 nanowires (1-D fillers) are dispersed in polyetherimide (PEI). We showed that 1-D fillers at ultra-low volume loading markedly enhance the dipolar response of PEI. While nanoparticles generate a spherical shell interface nanotopology, the cylindrical shell nanostructures generated by 1-D fillers are much more efficient at raising the dipolar response in terms of extending the high dielectric response of the interfacial region and reducing the influence of low-dielectric-constant polymer regions. Consequently, PEI nanocomposites with 0.75 vol.% of nanorods exhibit more than ten times enhanced dipolar response while maintaining a low dielectric loss. These results pave the way for engineering high-performance dielectric polymers for applications over a broad temperature range.

The work was published in X. Chen, T. Yang, Q. Zhang, L. Q. Chen, **V. Bobnar**, C. Rahn, Q. M. Zhang, Topological structure enhanced nanostructure of high temperature polymer exhibiting more than ten times enhancement of dipolar response, *Nano Energy* **88**, 106226 (2021).

Development of eco-friendly cellulose-graphene oxide thin-film composites for flexible energy-storage devices

Nanocomposite films were fabricated by incorporating graphene oxide (GO) into the TEMPO-oxidized cellulose nanofibrils (TCNF), and further subjected to the UV irradiation in a nitrogen atmosphere for GO reduction. The reduction of GO and its interactions with TCNF have been proven by ATR-FTIR, FESEM, UV–Vis, Raman, and XRD spectroscopy measurements. The resulting films with an increased mechanical storage modulus are mechanically stable up to 160 °C, while due to the Maxwell-Wagner polarization the dielectric constant strongly increases even at a low GO content. Thus, these mechanically strong, flexible, and thermally stable composites are suitable, cost-effective, alternative green materials for flexible energy-storage devices. Moreover, an environmentally benign method of GO reduction by UV irradiation is a substitute for harmful chemical processes that can be extendable to other nanocomposite biomaterials.

The work was published in Y. B. Pottathara, **V. Bobnar**, Y. Grohens, S. Thomas, R. Kargl, V. Kokol, High dielectric thin films based on UV-reduced graphene oxide and TEMPO-oxidized cellulose nanofibres, *Cellulose* **28**, 3069 (2021).

Nanostructured multiferroic $Pb(Zr,Ti)O_3$–$NiFe_2O_4$ thin-film composites

Multiferroic thin-film composites were developed by embedding ferromagnetic $NiFe_2O_4$ into self-assembled porous ferroelectric $Pb(Zr,Ti)O_3$ thin films. Although bi- or multi-layers of spinel ferrites and $Pb(Zr,Ti)O_3$ were already fabricated, or, alternatively, their composites were prepared by sol-gel or RF sputtering techniques, the morphology

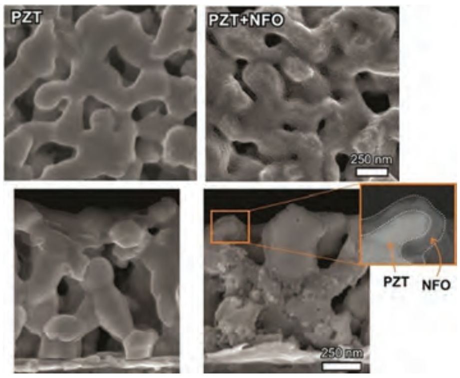

Figure 11: Structures of porous $Pb(Zr,Ti)O_3$ thin films that exhibit an extremely high piezoelectric response, and $Pb(Zr,Ti)O_3$-$NiFe_2O_4$ thin-film composites with an extensive contact area between the magnetostrictive and piezoelectric components. Scanning electron microscope images of film surfaces (top) and their cross-section (bottom).

of our system provides a very extensive connectivity between the magnetostrictive and piezoelectric constituents. Detailed structural investigations revealed a pure two-phase system, without any chemical reaction or solid solubility between the constituents. The multiferroicity of composites was evidenced by detecting both ferroelectric and ferromagnetic hysteresis loops. A measurable magnetic field–induced changes of the dielectric constant, not only at low frequencies but also above the characteristic frequencies of the Maxwell-Wagner behaviour, indicating a direct stress coupling between the magnetostrictive $NiFe_2O_4$ and piezoelectric $Pb(Zr,Ti)O_3$ grains and implies the potential utility of the developed material in magnetocapacitive applications.

The work was published in **A. Matavž**, **P. Koželj**, M. Winkler, K. Geirhos, P. Lunkenheimer, **V. Bobnar**, Nanostructured multiferroic $Pb(Zr,Ti)O_3$–$NiFe_2O_4$ thin-film composites, *Thin Solid Films* 732, 138740 (2021).

3.4 Functional quantum materials

Denis Arčon and his colleagues from France, Germany and Greece continued their research on $C_{59}N$ fullerene radicals trapped in cycloparaphenylene (CPP) rings. In the article by Y. Tanama et al., "Robust coherent spin centers from stable azafullerene radicals entrapped in cycloparaphenylene rings", *Nanoscale* 13, 19946-19955 (2021) they investigated the mechanism of formation of stable radicals in a solid. The method of electron paramagnetic resonance showed that the formation of extremely long-lived $C_{59}N$ radicals takes place in two stages and that monomeric radicals are formed only at temperatures above 150°C. The most important part of this study, however, concerned the potential use of $C_{59}N$ radicals as qubits. Namely, with the method of pulsed electron paramagnetic resonance, they showed that the coherence times of such centres are extremely long and that they enable, for example, the observation of Rabi oscillations over extended time periods. The article also suggested the possible directions for the development of such materials, where complex networks of interconnected fullerene qubits could be created.

Denis Arčon and his colleagues from Tohoku University in Japan continued their research on the $BaMn_2Pn_2$ system (where Pn = pniktid element). These systems form the same structures as the well-known $BaFe_2As_2$ superconductors and are therefore also interesting from the point of view of understanding superconductivity. In two publications, T. Ogasawara et al. *Phys. Rev. B* 103, 125108 (2021) and N. Janša et al., *Phys. Rev. B* 103, 064422 (2021) they reported the discovery of an extremely complex temperature-dependent giant magnetoresistance. Through a combination of different experimental techniques, they have shown that a multi-orbital electronic structure is crucial for the emergence of such giant magnetoresistance. Four of the Mn 3d orbitals are important for magnetic order, while the narrow band derived from the fifth Mn 3d orbital is responsible for the transport properties themselves. It turns out that the holes in this last orbital localize below a temperature of 50 K and then form a short-range order and appear essential for the occurrence of a magnetoresisitve response.

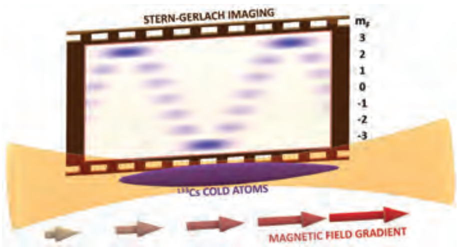

Figure 12: Illustration of the magnetic gradiometer showing a Stern-Gerlach image of an elongated caesium cold-atom cloud expanding along the laser beam.

4. Cold atoms

Katja Gosar, **Tina Arh**, **Tadej Mežnaršič**, **Ivan Kvasić**, **Dušan Ponikvar**, **Tomaž Apih**, **Erik Zupanič**, and **Peter Jeglič** demonstrated a novel method for detecting the gradient of a magnetic field using an elongated cloud of caesium atoms cooled to near absolute zero. Since the rotation of the atomic spins depends on the magnetic field, an image of the spin states can be used to measure how the magnetic field changes along the cloud. The gradient is determined from a single image, which is an advantage over standard methods where multiple images are needed. The method was published in K. Gosar *et al.*, "Single-shot Stern-Gerlach magnetic gradiometer with an expanding cloud of cold cesium atoms", *Phys. Rev. A* 103, 022611 (2021).

II. Research Programme: Physics of Soft Matter, Surfaces, and Nanostructures

We demonstrated the tuneable emission of structured light from liquid-crystal (LC) microlasers and the reversible transformation of liquid-crystal droplets into fibres and objects of other shapes. We have shown that topological defects in LCs can separate the electric charge and that even spherical particles exhibit anisotropic electrostatic interactions in LCs.

The investigations of the research programme ***Physics of Soft Matter, Surfaces, and Nanostructures*** focuses on novel complex soft-matter systems and surfaces with specific functional properties. The aim of the programme is to understand the structural and dynamical properties of these systems, their interactions, their function at the molecular level, and self-assembly mechanisms in soft matter. The underlying idea is that it is possible to understand complex mechanisms, such as self-assembly, on a macroscopic level, using a simplified physical picture and models. To provide a comprehensive approach to the problem, the program combines both experimental and theoretical investigations, supported by modelling and simulations. Special emphasis is given to possible electro-optic and medical applications.

Topological liquid-crystal superstructures as structured light lasers

Liquid crystals form an extremely rich range of self-assembled topological structures with artificially or naturally created topological defects. Liquid crystals have been used before inside laser cavities; however, until now only relatively simple liquid-crystal structures have been employed. Our study provides experimental and simulation insights into the coupling of light with the complex liquid-crystal topological superstructures inside a laser cavity. This results in non-trivial intensity and polarization of the generated structured light. The proposed soft-matter-microlaser approach opens a new direction in soft-matter photonics research. The work performed in a collaboration with the Faculty of Mathematics and Physics at the University of Ljubljana was published in the Proceedings of the National Academy of Sciences of the United States of America (PNAS 2021, DOI: 10.1073/pnas.2110839118).

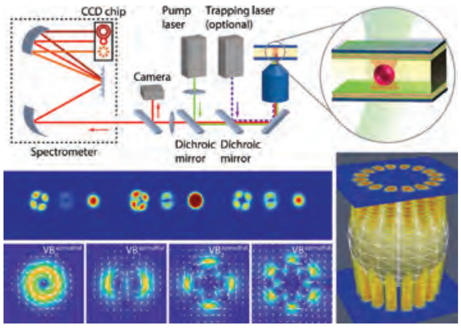

Figure 13: Optical setup used in the experiments (top) and a few examples of the experimentally generated and simulated vector laser beams (bottom).

Elasticity-driven self-shaping liquid-crystal emulsions

We present a universal concept for the shape transformation of liquid-crystal (LC) droplets suspended in aqueous surfactant solutions. The key novelty is dynamically tuning the interfacial tension to the minimum with temperature using an anionic surfactant dispersed in a LC medium and a cationic surfactant dispersed in an aqueous continuous medium. The successful reduction of the tension coupled to the tuning of the bulk LC elastic constants with the temperature drives the LC droplet into controllable self-shaping fibre structures with branches and back reversibly. We hypothesize the reversible self-shaping phenomenon is caused by the surfactant migration to the LC/water interface and forming a surfactant layer that is sensitive to temperature. The growth is induced by negative interfacial tension, which promotes a spontaneous increase of the interfacial area. Moreover, the nematic-to-SmA LC phase transition drives the fibre structures into monodispersed micro-droplets with a tuneable diameter dictated by the cooling rate. The extension of the self-shaping phenomenon in the SmC phase opens the route to generate helical fibres. Moreover, the SmA* phase shows life-like self-shaping LC shell structures analogous to the bio-membranes in living systems. A theoretical model for transforming LC emulsions into uniform fibres and vice versa is also presented. The research, performed in collaboration with researches from Gottingen, San Diego, Tokyo, and Luxembourg, was published in the PNAS, DOI: 10.1073/pnas.2011174118.

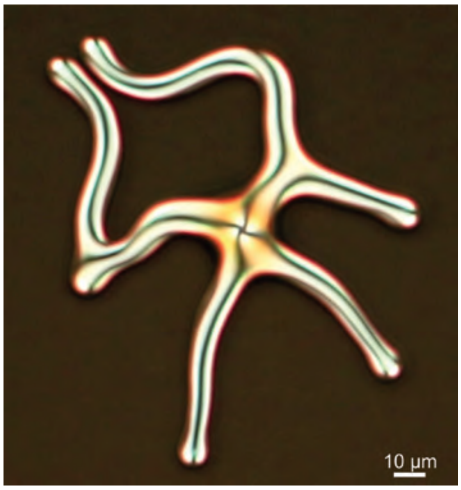

Figure 14: Self-shaping nematic fibres and droplets.

Ionically charged topological defects in nematic fluids

The ability to spatially control the electric charge is important in different fields, ranging from charged polymers, biological and active substances to colloidal materials, complex liquids and microelectronics. We showed with theoretical-simulation approaches that topological defects in nematic electrolytes can act as areas for the local separation of electric charge, forming electrically charged defective nuclei and, in selected geometries, electrical multi-layers, which is a generalization of electrical double layers in isotropic electrolytes. In particular, they showed that ions couple very efficiently with defect cores via ionic solubility, and with the surrounding orientation field through the flexoelectricity mechanism. The achievement contributes to the understanding of electrostatic mechanisms in topologically soft matter, and at the same time is a step towards understanding similar phenomena in biological systems that have a much more complex structure and composition. The research was conducted in collaboration with the Faculty of Mathematics and Physics at the University of Ljubljana and was recognized as one of the most prominent research achievements of 2021 by the Public Research Agency of the Republic of Slovenia within the program "Excellent in Science 2021" (Physical Review X 2021, DOI:10.1103/PhysRevX.11.011054).

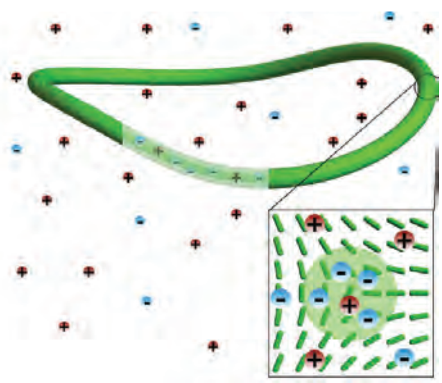

Figure 15: Ionically charged topological defects in nematic fluids.

Anisotropic electrostatic screening of charged colloids in nematic solvents

The physical behaviour of anisotropic charged colloids in nematic solvents is determined by their material dielectric anisotropy demonstrated anisotropic electrostatic screening for charged colloidal particles in a nematic electrolyte. The electrostatic potential and pair interactions decay with an anisotropic Debye screening length, contrasting the constant screening length for isotropic electrolytes. Charged dumpling-shaped near-spherical colloidal particles in a nematic medium are used as an experimental model system, demonstrating competing anisotropic elastic and electrostatic effective pair interactions for colloidal surface charges tuneable from neutral to high, yielding particle-separated metastable states. Generally, the work contributes to an understanding of electrostatic

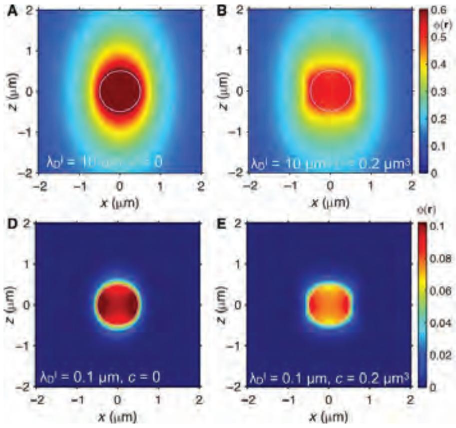

Figure 16: Anisotropic electrostatic screening of charged colloids in nematic solvents.

screening in nematic anisotropic media. The research, done in collaboration with researchers from Physics at Universities of Ljubljana and Boulder, was published in Science Advances 2021, DOI: 10.1126/sciadv.abd0662.

Whispering-gallery-mode sensors for biological and physical sensing

In a review paper published in Nature Reviews Methods Primers we, in the collaboration with researchers from the Universities of Exeter, Michigan, and Okinawa, introduce whispering-gallery-mode microcavities in different geometries, such as microspheres, microtoroids, microcapillaries and microrings. Whispering-gallery-mode microcavities are miniature micro-interferometers that use the multiple-cavity passes of light for very sensitive measurements at the microscale and nanoscale, including single-molecule and ion measurements. We describe sensing mechanisms, including mode splitting and resonance shift, and optomechanical and optoplasmonic signal transductions. Applications and experimental results cover in-vivo and single-molecule sensing, gyroscopes and microcavity quantum electrodynamics (*Nat Rev Methods Primers* 2021, DOI: 10.1038/s43586-021-00079-2).

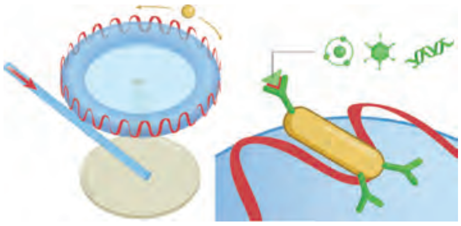

Figure 17: Principle of operation of an optical microresonator and sensing based on the binding of various molecules.

Dual-frequency electrically driven nematic microstructures confined to biaxial porous polymer membranes

We report a study of internal ordering and the electro-optical response of dual-frequency nematic liquid crystals (DFNLCs) confined to microporous polyethylene terephthalate (PET) membranes. The DFNLCs are characterized by positive/negative signs of dielectric anisotropy in low/high-frequency electric fields. Low/high-frequency electric fields were applied to the PET-DFNLC membrane to manipulate the internal nematic configuration. We found that the low/high-frequency electric fields drive a structural transformation resulting in the suppressed/increased propagation of near-infrared electromagnetic radiation through a composite material. The results are discussed for photonic applications. The study has been performed in collaboration with researchers from Moscow and published in Applied Physics Letters 2021, DOI: 10.1063/5.0069056.)

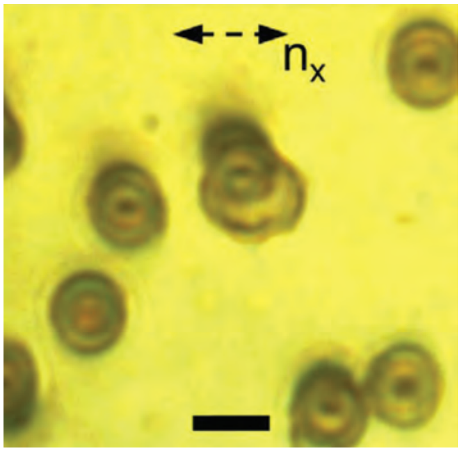

Figure 18: Microscopic texture of a DFNLC confined to microporous PET membranes.

Pretransitional Effects of the Isotropic Liquid–Plastic Crystal Transition

We report on strong pretransitional effects across the isotropic liquid–plastic crystal melting temperature in linear and nonlinear dielectric response. Studies were carried out for cyclooctanol in the unprecedented range of temperatures 120 K < T < 345 K. Such pretransitional effects have not yet been reported in any plastic crystals. We compare the observed pretransitional behaviour with the one observed in 8OCB (a typical liquid-crystal representative), displaying a reversed sequence of phase transitions in orientational and translational degrees of order on varying the temperature. Furthermore, in its nematic phase, we demonstrate the first-ever-observed temperature-driven crossover between regions dominated by an isotropic liquid and smectic A pretransitional fluctuations. We propose a pioneering minimal model describing plastic crystal phase behaviour where we mimic the derivation of classical Landau-de Gennes-Ginzburg modelling of Isotropic-Nematic-Smectic A LC phase behaviour. The study has been performed in collaboration with researchers from Warsaw and published in Molecules 2021, *DOI:* 10.3390/molecules26020429.

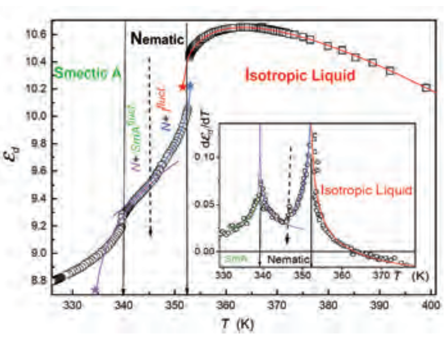

Figure 19: Dielectric response as a function of temperature.

Co-revolving topological defects in a nematic liquid crystal

A patterned surface defect of strength m = 1 and its associated disclination lines can decompose into a pair of surface defects and disclination lines of strength m = 1/2. For a negative dielectric anisotropy liquid crystal subjected to an applied ac electric field *E*, these half-integer defects are observed to wobble azimuthally for *E* less than some threshold field and, for sufficiently large fields, to co-revolve antipodally around a central point approximately midway between the two defects. This behaviour is elucidated experimentally as a function of the applied field strength and frequency. A complete field vs. frequency "phase diagram" compellingly suggests that the induced fluctuations and eventual co-revolutions of the defects are driven by the hydrodynamic instability. The observed behaviour suggests a Lehmann-like mechanism that drives the co-revolution. The study was made in collaboration with researchers from Cleveland (Soft Matter 2021, *DOI:* 10.1039/D1SM01124C).

Minimum dissipation theorem for microswimmers

Biological or artificial microswimmers propel themselves through a fluid in the low-Reynolds-number regime either by periodically changing their shape or by inducing an effective slip velocity along their surface. We have derived a minimum dissipation theorem for microswimmers. It provides a lower bound on the power needed by an active swimmer, expressed with the drag coefficients of two passive bodies of the same shape: one with a no-slip and one with a perfect-slip boundary. The theorem holds for swimmers of any shape, moving with any translational and/or rotational velocity. The proof involves a generalization of the Helmholtz minimum dissipation theorem, the principle of linear superposition and the Lorentz reciprocal theorem. We also show that the optimal swimmer has the velocity profile of the perfect-slip body (e.g., a gas bubble) and the tangential traction of the no-slip body. We have thus reduced a seemingly complex optimization problem to the calculation of two passive drag coefficients. The study was mostly performed at the Max Planck Institute for Dynamics and Self-Organization in Göttingen (Phys. Rev. Lett. 2021, DOI: 10.1103/PhysRevLett.126.034503).

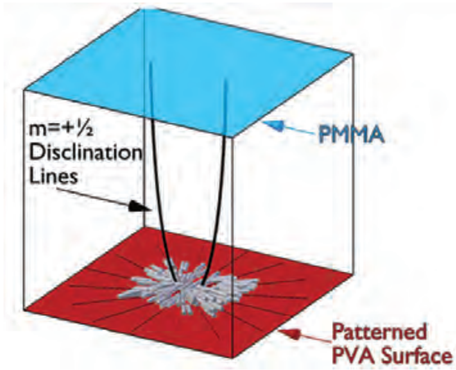

Figure 20: Surface topology nucleated disclinations.

Ciliary chemosensitivity is enhanced by cilium geometry and motility,

Primary cilia, which are usually immotile, have primarily sensory functions as receptors for chemical or mechanical signals. However, there is mounting evidence that the sensory functions are not limited to immotile cilia and that beating cilia can also contain chemical receptors. This raises the question as to whether there is a physical advantage in placing chemical receptors on a cilium in terms of sensitivity. To answer this question, we studied the capture rates of signalling particles on a model cilium embedded in a flat surface. We showed that, even in a quiescent fluid with no advection, the cilium already achieves the same capture rate as a surface patch with 4 times the surface area. When the cilium is placed in an external shear flow, the equivalent surface ratio rises to 6 times. A motile cilium can achieve a significant enhancement of the capture rate at high Péclet numbers, but only if it beats in a non-reciprocal way and thus induces a long-range net flow in the surrounding fluid. When many immotile cilia are placed in proximity, the capture rate per cilium is reduced because of the depletion of the concentration field. However, when the same cilia beat asymmetrically, their capture rate is enhanced by the flow generated by the surrounding cilia. The study was mostly performed at the Max Planck Institute for Dynamics and Self-Organization in Göttingen (eLife 2021, DOI: 10.7554/eLife.66322).

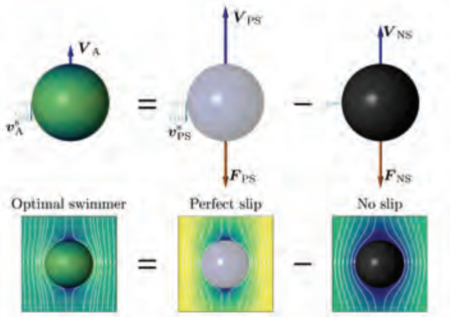

Figure 21: The optimal active microswimmer can be represented as a superposition of the flow around a perfect slip body and that around a no-slip body (shown for a spherical swimmer).

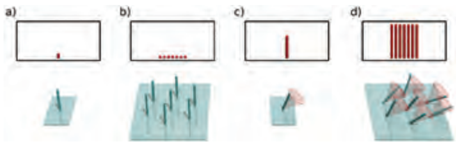

Figure 22: The particle capture rate per cilium (length of red bars) for: (a) an isolated immotile cilium, (b) a group of 7 immotile cilia, (c) an isolated beating cilium and (d) a group of 7 beating cilia. While the capture rate in a group of immotile cilia is reduced due to depletion, motile cilia benefit from mutual enhancement by the generated flow.

New W_nO_{3n-1} stoichiometric phase

We synthesized and characterized tungsten suboxide crystals, which grow in the form of nanotiles. Three new stoichiometric phases were determined from high-resolution TEM images: $W_{13}O_{38}$ ($WO_{2.923}$), $W_{12}O_{35}$ ($WO_{2.917}$) in $W_{11}O_{32}$ ($WO_{2.909}$). The experimental unit-cell parameters were in agreement with the calculated ones. The nanotiles have a distinct zig-zag morphology, with corrugation that are several 10 nm deep. The valence band spectrum showed some density of states at the Fermi energy, making the material slightly metallic (Nanomaterials 2021, DOI: 10.3390/nano11081985).

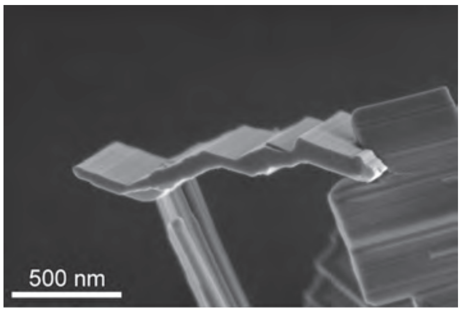

Figure 23: The WO_{3-x} plates in a form of nanotiles.

Filtration efficiency of respiratory masks used during the COVID-19 pandemic

We performed size- and time-dependent filtration-efficiency measurements of face masks and improvised respiratory protection equipment used during the COVID-19 pandemic. The results showed the high filtration efficiency of FFP2, FFP3, and certified surgical masks for all sizes of tested particles, while the filtration efficiency of washable masks depended on their constituent fabrics. The filtration efficiency for the FFP2 fabric was above 98.6%, while for the FFP3 fabric it was above 99.9%. Similar or slightly lower filtration-efficiency values were observed for tested materials obtained from different surgical masks. Different cotton materials that are usually used in cotton masks had the filtration efficiency between 26% and 82%, mainly due to the large diameter of the cotton fibres, which also lack any static charge. The study was done in collaboration with researchers from the Department of Physics at the University of Ljubljana and industry (Sensors 2021, DOI: 10.3390/s21051567).

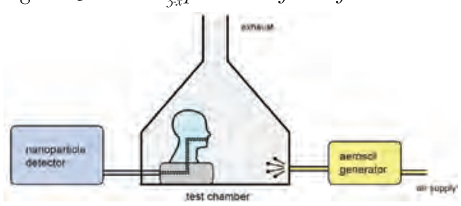

Figure 24: Schematic representation of the measurement of filtration efficiency for respiratory masks during the COVID-19 pandemic.

Tuning graphene doping by carbon monoxide intercalation at the Ni(111) interface

Under near-ambient pressure conditions, carbon monoxide molecules intercalate underneath an epitaxial graphene monolayer grown on Ni(111), getting trapped into the confined region at the interface. On the basis of ab-initio density functional theory calculations, we provided a full investigation of the intercalated CO pattern, highlighting the modifications induced on the graphene electronic structure. The most relevant signature of the CO intercalation is a clear switching of the graphene doping state, which changes from n-type, when strongly interacting

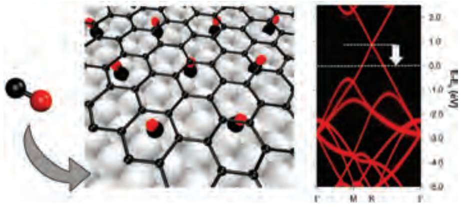

Figure 25: Carbon monoxide intercalated at a graphene/Ni(111) interface forms periodic patterns, decouples the graphene from the Ni(111) and shifts the Dirac cone up to about 1 eV.

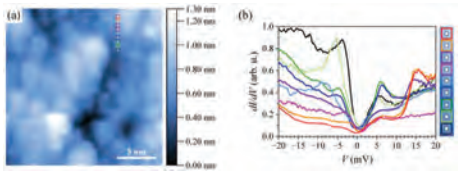

Figure 26: Topographic STM image of the HTZS-Nb sample surface and the corresponding dI/dV curves showing a varying superconducting gap.

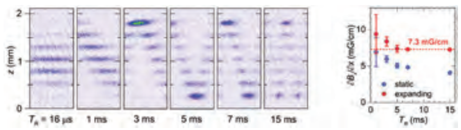

Figure 27: (a) Absorption images of position-dependent mF-state populations for a range of interrogation times and (e) the extracted component of the magnetic-field gradient.

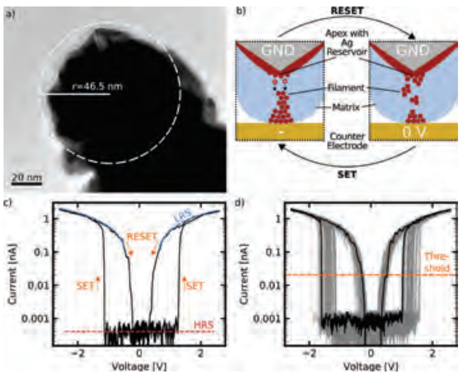

Figure 28: (a) TEM image of a memtip indicating a radius of curvature of 46.5 nm. (b) Schematics of SET and RESET operations. The current in the low resistive state (LRS) is limited by the 1-GΩ serial resistor incorporated into the experimental setup. The high resistance state (HRS) is given by the detection limit of the setup. (c) and (d) Representation of a single and 100 sequential cycles showing a consistent switching window. A threshold level of 20 pA, as indicated, is chosen for a reliable detection of SET and RESET.

with the metal surface, to p-type. The shift of the Dirac cone linearly depends on the CO coverage, reaching about 0.9 eV for the saturation value of 0.57 ML. Theoretical predictions are compared with the results of STM, LEED and XPS experiments, which confirm the proposed scenario for the nearly saturated intercalated CO system. The paper was published in collaboration with groups from Italy (*Carbon 2021,* DOI: 10.1016/j.carbon.2021.01.120).

Structure and Superconductivity of Tin-Containing HfTiZrSnM (M = Cu, Fe, Nb, Ni) Medium-Entropy and High-Entropy Alloys

In an attempt to incorporate tin into high-entropy alloys composed of the refractory metals Hf, Nb, Ti and Zr with the addition of the 3d transition metals Cu, Fe, and Ni, we synthesized a series of alloys in the system HfTiZrSnM (M = Cu, Fe, Nb, Ni). The alloys were characterized crystallographically, microstructurally, and compositionally, and their physical properties were determined, with the emphasis on superconductivity. A common feature of the alloys is a microstructure of large crystalline grains of a hexagonal (Hf, Ti, Zr)5Sn3 partially ordered phase embedded in a matrix that also contains many small inclusions. Based on the electrical resistivity, specific heat, and magnetization measurements, a superconducting (SC) state was observed in the HfTiZr, HfTiZrSn, HfTiZrSnNi, and HfTiZrSnNb alloys. The HfTiZrSnFe alloy shows a partial SC transition, whereas the HfTiZrSnCu alloy is non-superconducting. A paper was published in collaboration with groups from Poland, China and Sweden (*Materials, 2021,* DOI: 10.3390/ma14143953).

Single-shot Stern-Gerlach magnetic gradiometer with an expanding cloud of cold caesium atoms

We combined the Ramsey interferometry protocol, the Stern-Gerlach detection scheme, and the use of the elongated geometry of a cloud of fully polarized cold caesium atoms to measure the selected component of the magnetic-field gradient along the atomic cloud in a single shot. In contrast to the standard method where the precession of two spatially separated atomic clouds is simultaneously measured to extract their phase difference, which is proportional to the magnetic-field gradient, we show a gradiometer using a single image of an expanding atomic cloud with the phase difference imprinted along the cloud. Using resonant radio-frequency pulses and Stern-Gerlach imaging, we first demonstrate nutation and Larmor precession of atomic magnetization in an applied magnetic field. Next, we let the cold atom cloud expand in one dimension and apply the protocol for measuring the magnetic-field gradient. The resolution of our single-shot gradiometer is not limited by the thermal motion of atoms and has an estimated absolute accuracy of better than ±0.2 mG/cm (±20 nT/cm). (*Phys. Rev. A, 2021,* 10.1103/PhysRevA.103.022611)

Correlations and filamentary dynamics in nanoscale memristor

To emulate the neural dynamics of excitatory and inhibitory processes, memristors offer a practical hardware approach to implement such functionalities for possible utilization in efficient probabilistic computation. In an attempt to unravel the intrinsic long-range dynamics at room temperature, while mitigating the unwanted thermal drift, we focus on nanoscale memristor built at the apex of a scanning probe tip. With the design of such functionalized cantilevers (entitled here as "memtips") we captured the long-term intrinsic current response, identified temporal correlations between switching events and observed emerging spiking dynamics directly at the nanoscale. Utilization of an identical memtip for measurements on different counter electrodes made it possible to directly compare the impact of different device configurations on the switching behaviour of the same filament. Such an analytical approach in ambient conditions will pave the way towards a deeper understanding of filamentary switching phenomena on the nanoscale. The study was conducted in collaboration with researchers from the University of Kiel and published in *Nanomaterials* **2021**, DOI: 10.3390/nano11020265.

III. Research programme: Experimental biophysics of complex systems and imaging in biomedicine

The programme group **Experimental biophysics of complex systems and imaging in biomedicine** combines research of the processes and structures of biological systems by developing new, advanced experimental techniques of super-resolution microscopies, microspectroscopies and nanoscopies as well as new imaging techniques. Our research is mainly focused on the response of molecular and supramolecular structures to interactions between materials and living cells as well as between light and living cells. We are interested in molecular events and physical mechanisms with which these events are causally connected, time scales, conditions and applied value of the investigated mechanisms, especially for use in medicine and in the field of healthcare in general. With the development of new, coupled, super-resolution and spectroscopic techniques we want to open new possibilities to investigate biological systems and from there onwards to open new possibilities for designing medical materials and devices, for diagnostics, therapy and tissue regeneration, representing key challenges due to the population aging. The investment into the new super-resolution STED system opened a variety of fluorescence microscopy approaches: STED microscopy and two-photon (2PE) microscopy, multichannel spectrally resolved fluorescence lifetime imaging (spFLIM), fluorescence microspectroscopy (FMS). These, coupled with optical tweezers, can be used to examine the interactions between materials, nanomaterials and cell lines and the phenomena involved such as lipid wrapping and nanomaterial passivation, membrane disintegration, and cellular membrane translocation bypassing conventional signalling pathways. We also introduced a method that makes possible the monitoring of the electric field in tumours in the treatment of cancer with electroporation, and further developed a method of multiparametric magnetic resonance imaging for the characterization of food and medicines and various industrial processes. High resolution magnetic resonance imaging can monitor the effectiveness of surface treatments, the formation and dissolution of gels as well as measure diffusion in confined geometries with the use of modulated gradients.

After founding the spin-off company Infinite d.o.o. on the basis of our own breakthrough ideas, the company acquired its first start-up investment in 2021, and with it already supported further basic and applied research in the field of disease-triggering mechanisms.

In 2018, in Nano Letters, we proposed a causal link between the inhalation of nanoparticles and cardiovascular disease based on the presence of coagulation enzymes tissue factor, factor X, and plasma membrane lipids in the corona of TiO_2 nanoparticles after exposure to lung epithelial cells. To further **elucidate the role of lipids in the activation of factor X**, we used soluble forms of PS and PE (1,2-dicaproyl-sn-glycero-3-phospho-l-serine (C6PS), and 1,2-dicaproyl-sn-glycero-3-phospho-ethanolamine (C6PE). We found that two molecules of each lipid bind independently to factor VIIa, with a dissociation constant of around 150 μM, increasing the rate of activation of factor X by about 100-fold in the presence of a soluble tissue factor. The work was published in Podlipec, Rok, Mur, Jaka, Petelin, Jaka, Štrancar, Janez, Petkovšek, Rok. Method for controlled tissue theranostics using a single tunable laser source. Biomedical optics express, ISSN 2156-7085, 2021, vol. 12, no. 9, pp. 5881-5893, doi: 10.1364/BOE.428467.

To prevent experimental artefacts by poorly fluorescently labelled metal oxide nanoparticles – the largest subpopulation of nanoparticles by industrial production and applications – in live-cell imaging, we introduced a **set of experimental methods to enable artefact-free fluorescent labelling** and demonstrated its application in the case of TiO_2 nanotubes. We characterized potential changes of the nanoparticles' surface charge and morphology that might occur during labelling by using zeta-potential measurements and transmission electron microscopy and assessed the stable binding of the fluorescent dye to the nanoparticles with either fluorescence intensity measurements or fluorescence correlation spectroscopy, which ensures reliable nanoparticle localization within living cells. The work was published in Kokot, Boštjan, Kokot, Hana, Umek, Polona, Van Midden, Katarina Petra, Pajk, Stane, Garvas, Maja, Eggeling, Christian, Koklič, Tilen, Urbančič, Iztok, Štrancar, Janez. How to control fluorescent labeling of metal oxide nanoparticles for artefact-free live cell microscopy. Nanotoxicology, ISSN 1743-5404, 2021, vol. 15, no. 8, pp. 1102-1123, doi: 10.1080/17435390.2021.1973607.

Within the industrial cooperation with our spin-out company Infinite d.o.o.we have enabled the live observation of **new, early molecular events** followed by exposure of our in-vitro lung barrier. We have identified some events that appear **earlier than the quarantine of nanomaterials** and could become the key events for the even faster prediction of long-term health complications. Among them, we discovered the surfing nanomaterials and gap formation, for which we are still looking for the causal connections with other known events. In addition, we have **upgraded the back-scattered microscope detection of particulate matter** on the fluorescence microscopes to enable label-free tracking of particles.

As a part of two PhD research projects, we have firstly developed **the novel concept of dose**, which advances the concept of local dose including the information on local interactions. Secondly, we have observed nanomaterial-triggered changes in neurons', where the importance of **immune cells** was even greater than in the case of lung barrier exposure. The latter seem to be **crucial for the survival of neurons**. These two doctoral dissertations will be defended in 2022.

Successful research work conducted within the framework of the ARRS project Spatial and temporal design of laser light for minimally invasive ophthalmic procedures (L2-9254), was rewarded with the publication in the first-quartile journal Biomedical Optics Express [1]. The study reports on **a new teranostic method for detecting the effect of laser therapy on ocular tissues** in real-time based on measurements and the **analysis of fluorescence lifetime** and the use of a **powerful adaptive 2-photon laser system** developed in the Laboratory of Photonics and Laser Systems (FOLAS), Faculty of Mechanical Engineering, University of Ljubljana. For the research work within the ARRS project L7-7561, an official publication was rewarded to the granted European patent (EP3755994B1)

Štrancar, Janez, Podlipec, Rok, Urbančič, Iztok, Arsov, Zoran, Vrečko, Andrej. Image-processing apparatus and image-processing method for detection of irregularities in tissue: European patent specification EP 3 755 994 B1, 2021-05-26. Munich: European Patent Office, 2021. 23 pp.,

In cooperation with the Laboratory of Thermal Engineering (LTT), Faculty of Mechanical Engineering and the Department of Pharmaceutical Chemistry, Faculty of Pharmacy, we conducted new studies for the detection and analysis of temperature dynamics in the micro-boiling processes with new preparation methods and new combinations of the developed temperature-sensitive organic and inorganic molecules. Based on the results of the research, we are preparing a scientific publication planned for 2022.

Within the Crossing Borders and Scales (CROSSING) project, we continued to study new approaches and **optimize protocols for correlative microscopy** on relevant biological systems using new high-resolution microscopes and spectroscopes (synchrotron soft XRF, cryo micro-PIXE, etc.) with the ongoing ones. To study the mechanisms that lead to chronic inflammation of the lung epithelium due to nanoparticle exposure, we added time-dynamics measurements with high-resolution HIM microscopy in addition to the temporal dynamics of the interaction measured on living systems. The results of the study will be published in 2022 in a journal with a high impact factor. In collaboration with the Department of Low and Medium Energy Physics (F2) and the Department of Orthopedics, University Medical Center Maribor, we conducted a study to understand the negative impact of the metal wear debris from hip prosthesis on the surrounding tissue, potentially leading to an immune response. Using some of the most advanced high-resolution and sensitive microscopes and spectroscopes available at the JSI and HZDR, we directly identified, among other things, wear-debris-induced oxidative stress, which can cause chronic inflammation. All the findings were published in Podlipec, Rok, Punzón Quijorna, Esther, Pirker, Luka, Kelemen, Mitja, Vavpetič, Primož, Kavalar, Rajko, Hlawacek, Gregor, Štrancar, Janez, Pelicon, Primož, Fokter, Samo K. Revealing inëammatory indications induced by titanium alloy wear debris in periprosthetic tissue by label-free correlative high-resolution ion, electron and optical microspectroscopy. Materials, ISSN 1996-1944, 2021, vol. 14, issue 11, pp. [1-16], doi: 10.3390/ma14113048.]. Using complementary imaging methods, we also participated in a published study focused on the effects of toxic nanoparticles on freshwater organisms in Schymura, Stefan, Drev, Sandra, Podlipec, Rok, Rijavec, Tomaž, Lapanje, Aleš, Štrok, Marko, et al. Dissolutionbased uptake of nanoparticles by freshwater shrimp: a dual-radiolabelling study of the fate of anthropogenic cerium in water organisms. Environmental science, Nano, ISSN 2051-8161, 11 pp., doi: 10.1039/d1en00264c.

We kept developing advanced microscopy and microspectroscopy techniques and applied them to elucidate diverse molecular and cellular mechanisms. We used Eu-doped TiO_2 nanoparticles as intracellular temperature sensors, as described in Urbančič, Iztok et al. Aggregation and mobility of membrane proteins interplay with local lipid order in the plasma membrane of T cells. FEBS Letters. [Online ed.]. [in press]2021, 20 pp. ISSN1873-3468. DOI: 10.1002/1873-3468.14153. In collaboration with the University of Oxford (UK), we unravelled how **membrane lipids and proteins interplay to support the activation of T cells**; the contribution was featured as the cover story of the renowned journal *FEBS Letters* Havrdová, Markéta, Urbančič, Iztok, Bartoň Tománková, Kateřina, Malina, Lukáš, Štrancar, Janez, Bourlinos, Athanasios B. Self-targeting of carbon dots into the cell nucleus: diverse mechanisms of toxicity in NIH/3T3 and L929 cells. International journal of molecular sciences. 2021, vol. 22, no. 11, pp. 5608-1-5608-16. ISSN 1661-6596. DOI: 10.3390/ijms22115608. With partners from the University of Olomouc (CZ), we investigated the **uptake of carbon nanodots as potential cancer therapeutics** Biagiotti, Giacomo, Purić, Edvin, Urbančič, Iztok, Krišelj, Ana, Weiss, Matjaž, Mravljak, Janez, Gellini, Cristina, Lay, Luigi, Chiodo, Fabrizio, Anderluh, Marko, et al. Combining cross-coupling reaction and Knoevenagel condensation in the synthesis of glyco-BODIPY probes for DC-SIGN super-resolution bioimaging. Bioorganic chemistry. 2021, vol. 109, pp. 1-10, ilustr. ISSN 0045-2068, DOI: 10.1016/j.bioorg.2021.104730. We participated in the development of a new fluorescent probe to stain immune cells that is capable of super-resolution STED microscopy, published in Kokot, Boštjan, Kokot, Hana, Umek, Polona, Van Midden, Katarina Petra, Pajk, Stane, Garvas, Maja, Eggeling, Christian, Koklič, Tilen, Urbančič, Iztok, Štrancar, Janez. How to control the fluorescent labelling of metal oxide nanoparticles for artefact-free live cell microscopy. Nanotoxicology, ISSN 1743-5404, 2021, vol. 15, no. 8, pp. 1102-1123, doi: 10.1080/17435390.2021.1973607.

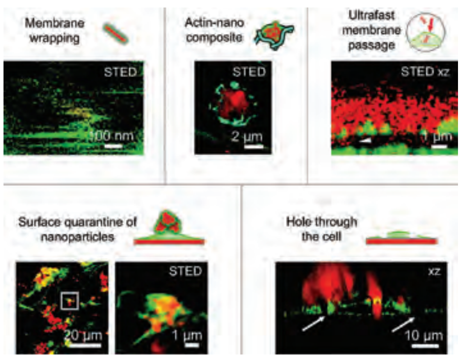

Figure 29: Examples of five early molecular events in living epithelial cells following exposure to nanomaterial (TiO_2 nanotubes labelled, red), detected with confocal or STED fluorescence microscopy. Other channels are context-related (green).

Study of magnetoliposomes as MRI contrast agents and drug-delivery systems

The Laboratory of Magnetic Resonance Imaging with our partners from the Department of Nanostructured Materials (K7, JSI) and international partners conducted a larger study on the effect of PD1 blockade on the therapeutic efficacy of novel doxorubicin-loaded temperature-sensitive liposomes. Studied were low temperature-sensitive magnetoliposomes for efficient drug delivery that can be photothermally activated. These magnetoliposomes also act as contrast agents for magnetic resonance imaging. The magnetoliposomes were prepared by embedding coated iron oxide nanoparticles (IO NPs) in the lipid bilayer of liposomes and loading the liposimes with the drug Doxorubicin. Our role in the study was to characterize the NMR relaxation properties of the magnetoliposomes and to image their accumulation in tumours of mice. It turned out that these magnetoliposomes are efficient T_2 NMR relaxation contrast agents with high transverse r_2 relaxivity of 333 mM^{-1} s^{-1}. Excellent contrast agent properties of the magnetoliposomes enables efficient MRI guidance of the drug delivery and therefore better and more efficient tumour therapy. The results of this study were published in a well-renowned journal in an article Ma Guanglong, Kostevšek Nina, Markelc Boštjan, Hudoklin Samo, Erdani-Kreft Mateja, Serša Igor, Čemažar Maja, Marković Katarina, Ščančar Janez et al. PD1 blockade potentiates the therapeutic efficacy of photothermally-activated and MRI-guided low temperature-sensitive magnetoliposomes. *Journal of controlled release*, ISSN 0168-3659, 2021, vol. 332, 45 pp., pp. 419-433, doi: 10.1016/j.jconrel.2021.03.002. We were also included in a similar study where instead liposomes erythrocyte membranes with embedded iron oxide nanoparticles were used. This study was published in an article: Kostevšek Nina, Miklavc Patricija, Kisovec Matic, Podobnik Marjetka, Al-Jamal Wafa, Serša Igor. Magneto-erythrocyte membrane vesicles' superior T_2 MRI contrast agents to magnetoliposomes. *Magnetochemistry*, ISSN 2312-7481, 2021, vol. 7, no. 4, pp. 51-1-51-14, doi: 10.3390/magnetochemistry7040051.

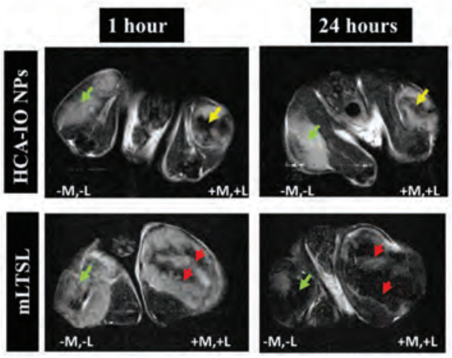

Figure 30: Low-temperature-sensitive magnetoliposomes as efficient T_2 NMR contrast agents in vivo. CT26 tumour-bearing mice were intravenously injected with coated iron oxide nanoparticles (HCA-IO NPs) or with low-temperature-sensitive magnetoliposomes with embedded coated iron oxide nanoparticles (mLTSL) at a Fe dose of 50 µg per mouse. After injection, one tumour was immediately taped with a magnet for 50 min and irradiated with the laser (808 nm, 0.3 W/cm2) for 10 min (+M, +L). The second tumour was not exposed to a magnet and was not irradiated (-M, -L). T_2-weighted images were taken 1 h and 24 h post-injection. Red and yellow arrows indicate darker contrast in treated tumours (+M, +L) injected with mLTSL and HCA-IO NPs, respectively. Green arrows indicate non-treated tumours (-M, -L). T_2-weighted MR images were recorded using the spin-echo sequences with parameters TE/TR = 40/3000 ms.

Magnetic resonance imaging of wood. Changes of the water state and its distribution in a beech sample while drying from the green (fresh cut) to the absolutely dry state were monitored by one-dimensional and two-dimensional ^{1}H NMR relaxometry as well as by spatial mapping of the NMR relaxation times T_1 and T_2. We found that the relaxometry results were consistent with the model of homogeneously emptying pores in a bioporous system with connected pores. This was also confirmed by the relaxation-time mapping results, which revealed the moisture transport in the course of drying from an axially oriented early- and latewood system to radial rays through which it evaporates from the branch. The results of this study confirmed that MRI is an efficient tool to study the pathways of water transport in wood while drying and is capable of determining the state of water and its distribution in wood. This study was published in an article: Mikac Urška, Merela Maks, Oven Primož, Sepe Ana, Serša Igor. MR study of water distribution in a beech (Fagus sylvatica) branch using relaxometry methods. *Molecules*, ISSN 1420-3049, 2021, vol. 26, no. 14, pp. 4305-1-4305-10, doi: 10.3390/molecules26144305. In addition to this study, we participated in another study on wood where we investigated the efficiency of the suppression of non-native tree species by stem wounding using incomplete girdling. This type of injury causes the plant to lose its vitality, become weaker after the first year and then die within a few years. Our task was to image the moisture distribution in the mechanically wounded stem. This study was published in an article: Plavčak Denis, Mikac Urška, Merela Maks. Influence of mechanical wounding and compartmentalization mechanism on the suppression of invasive plant species using the example of Cherry Laurel (Prunus laurocerasus). *Forests*, ISSN 1999-4907, 2021, vol. 12, iss. 2, 1-15 pp., ISSN 1999-4907, DOI: doi.org/10.3390/f12121646.

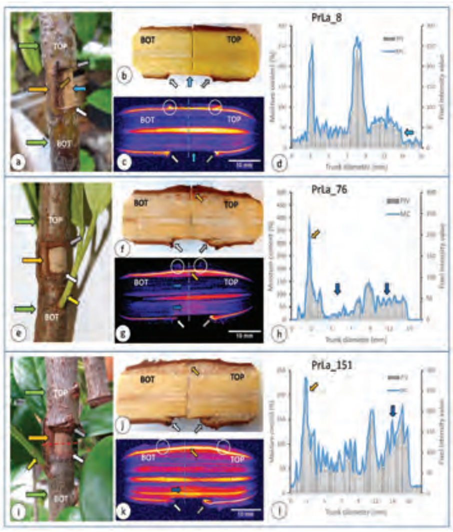

Figure 31: Injured stems of cherry laurel (Prunus laurocerasus) at day 8, 76 and 151 after mechanical wounding: (a,e,i) situation on the day of sampling; (b,f,j) bisected samples on the bottom (BOT) and top (TOP) part; (d,h,l) radial profile of moisture content calculated from MRI pixel intensity values, (c,g,k) Magnetic Resonance Image (MRI) of injured stems.

Correlations between the treatment outcome of ischemic stroke patients with X-ray properties of their thrombi. All the patients with a suspected stroke are directed to a whole-brain CT scan, which is used to look for early features of ischemia to locate the occlusion and its size, while the Hounsfield Units (HUs) values of the thrombus causing the stroke are usually overlooked. In this study we demonstrated that the HUs value is relevant and can help in better treatment planning for a stroke. The study included patients diagnosed with ischemic stroke in the middle cerebral artery (MCA). In all patients, systemic thrombolysis was not successful, and mechanical recanalization was needed. The retrieved thrombi were also analysed histologically for the determination of the red blood cells (RBCs) proportion. The CT scan of the proximal MCA segment was analysed for the average HU value and its variability both in the occluded section and the symmetrical normal site. Relevant positive correlations were found between the average HU value of thrombus and the treatment outcome evaluated by modified Rankin Scale (mRS), initial mRS, number of passes with thrombectomy device as well as RBC proportion. This study was published in an article: Viltužnik Rebeka, Vidmar Jernej, Fabjan Andrej, Jeromel Miran, Miloševič Zoran, Kocijančič Igor, Serša Igor. Study of correlations between CT properties of retrieved cerebral thrombi with treatment outcome of stroke patients. *Radiology and oncology*, ISSN 1318-2099. 2021, vol. 55, iss. 4, 409-417 pp., doi: 10.2478/raon-2021-0037.

MRI as a tool for monitoring the response of tissues to a pulsed electric field treatment. The aim of this study was to investigate the permeabilization of cell membranes in plant and animal foods (potatoes, apples, chicken) resulting from a treatment with a pulsed electric field. The study was performed at different amplitudes of electric pulses, and the results were expressed by changes in the electrical properties of tissues evaluated by electrical impedance spectroscopy, current-voltage measurements, and by magnetic resonance imaging. Imaged were changes in water distribution and in the T_2 NMR relaxation times. The findings of our research provide useful insights and could be in support of an appropriate choice of electroporation assessment methods in relation to the food-matrix characteristics. This study was published in an article: Genovese Jessica, Kranjc Matej, Serša Igor, Petracci Massimiliano, Rocculi Pietro, Miklavčič Damijan, Mahnič-Kalamiza Samo. PEF-treated plant and animal tissues: insights by approaching with different electroporation assessment methods. *Innovative food science & emerging technologies*, ISSN 1466-8564, 2021, vol. 74, 102872, pp. 1-9, doi: 10.1016/j.ifset.2021.102872.

The research of our department has been supported by a number of international projects financed by the European Union. It was also supported within many bilateral projects and other scientific cooperations. In 2021, the department had cooperations with 131 partners from Slovenia and abroad. Among them were the following institutions that made the reported studies possible:

1. A.F. Ioffe Physico-Technical Institute, Saint Petersburg, Russia
2. AEROSOL razvoj in proizvodnja znanstvenih instrumentov d.o.o., Ljubljana, Slovenia
3. AMES d.o.o., Brezovica pri Ljubljani, Slovenia
4. ART REBEL 9 d.o.o., Ljubljana, Slovenia
5. Balder, d. o. o., Ljubljana, Slovenia
6. BASF, Heidelberg, Germany
7. Ben Gurion University, Beersheba, Israel
8. BIA SEPARATIONS d.o.o., Ajdovščina, Slovenia
9. BTT TEKSTIL d.o.o., Zgornja Kungota, Slovenia
10. Centre national de la recherché scientifique, Laboratoire de Spectrochimie Infrarouge et Raman, Thiais, France
11. Centre national de la recherché scientifique, Laboratory de Marseille, Marseille, France
12. Chalmers University of Technology, Physics Department, Gothenburg, Sweden
13. Clarendon Laboratory, Oxford, Great Britain
14. CosyLab d.d., Ljubljana, Slovenia
15. Department of Chemistry, College of Humanities and Sciences, Nihon University, Tokyo, Japan
16. Deutsches Elektronen-Synchrotron, Hamburg, Germany
17. Deutsches Krebsforschungszentrum, Heidelberg, Germany
18. École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
19. Eidgenössische Technische Hochschule - ETH, Zürich, Switzerland
20. Elettra (Synchroton Light Laboratory), Basovizza, Italy
21. European Synchrotron Radiation Facility, Grenoble, France
22. Facultad de Ciencia y Technologia, Universidad del Pais Vasco UPV/EHU, Leioa, Spain
23. Faculty of Physics, Adam Mickiewicz University, Poznan, Poland
24. Florida State University, Florida, USA
25. Forschungszentrum Dresden Rossendorf, Dresden, Germany
26. Gunma National College of Technology, Maebashi, Japan
27. Helmholtz-Zentrum Dresden-Rossendorf e.V., Dresden, Germany
28. High Magnetic Field Laboratory, Nijmegen, the Netherlands
29. High Magnetic Field Laboratory, Tallahassee, Florida, USA
30. High-Magnetic-Field Laboratory, Grenoble, France
31. Humboldt Universität Berlin, Institut für Biologie/Biophysik, Berlin, Germany
32. Illie Murguescu Institute of Physical Chemistry of the Romanian Academy, Bucharest, Romania
33. Infineon Technologies Austria AG, Vienna, Austria
34. Infinite d.o.o., Limbuš, Slovenia
35. Institut für Biophysik und nanosystemforschung OAW, Graz, Austria
36. Institut für Experimentalphysik der Universität Wien, Vienna, Austria
37. Institut Ruđer Bošković, Zagreb, Croatia
38. Institute of Biophysics at the Faculty of Medicine, University of Ljubljana, Ljubljana, Slovenia
39. Institute of Crystallography, Moscow, Russia
40. Institute of Theoretical Physics, Göttingen, Germany

41. Institute of Electronic Materials Technology, Warsaw, Poland
42. Institute of Molecular Physics, Polish Academy of Sciences, Poznan, Poland
43. Instituto Superior Tecnico, Departamento de Fisica, Lisbon, Portugal
44. Instrumentation Technologies, d. d., Solkan, Slovenia
45. International Center for Theoretical Physics, Trieste, Italy
46. International Human Frontier Science Program Organisation, Strasbourg, France
47. ISIS, Rutherford Appleton Laboratory, Didcot, Great Britain
48. Kavli Institute for Theoretical Physics, Santa Barbara, USA
49. Kimberly Clark, Atlanta, USA
50. King's College, London, Great Britain
51. University Medical Center Ljubljana, Ljubljana, Slovenia
52. KMZ Zalar Miran s.p., CNC obdelava kovin in drugih materialov, Ljubljana, Slovenia
53. Korea Basic Science Institute, Daejeon, South Korea
54. Krka, tovarna zdravil, d.d., Novo mesto, Slovenia
55. KTH Royal Institute of Technology, Stockholm, Sweden
56. Kyung Hee University of Suwon, Impedance Imaging Research Center, Seoul, South Korea
57. L'Oreal, Paris, France
58. Lek farmacevtska družba d.d., Ljubljana, Slovenia
59. Liquid Crystal Institute, Kent, Ohio, USA
60. Lotrič Certificiranje d.o.o., Železniki, Slovenia
61. LPKF LASER & ELECTRONICS d.o.o., Naklo, Slovenia
62. LVL livarstvo in orodjarstvo d.o.o., Kranj, Slovenia
63. Max Planck Institut, Dresden, Germany
64. Mayo Clinic, Rochester, Minnesota, USA
65. Melamin kemična tovarna d.d., Kočevje, Slovenia
66. Merck KGaA, Darmstadt, Germany
67. Metalurško-kemična industrija Celje, d.d., Celje, Slovenia
68. MH Hannover, Hannover, Germany
69. Ministry of Defense of the Republic of Slovenia, Ljubljana, Slovenia
70. Nanotul d.o.o., Ljubljana, Slovenia
71. National Academy of Sciences of Ukraine, Institute of Physics, Kyiv, Ukraine
72. National Center for Scientific Research "Demokritos", Aghia Paraskevi Attikis, Greece
73. National Institute for Research in Inorganic materials, Tsukuba, Japan
74. Vinča Nuclear Research Institute, Belgrade, Serbia
75. Optotek d. o. o., Ljubljana, Tsukuba
76. Oxford University, Department of Physics, Department of Materials, Oxford, Great Britain
77. PAB Akrapović, Buzet, Croatia
78. Paul Scherrer Institut, Villigen, Switzerland
79. Politecnico di Torino, Dipartimento di Fisica, Torino, Italy
80. Radbound University Nijmegen, Research Institute for Materials, Nijmegen, the Netherlands
81. RLS Merilna tehnika d. o. o., Žeja pri Komendi, Slovenia
82. Rwth Aachen University, Aachen, Germany
83. School of Physics, Hyderabad, Andhra Prades, India
84. SISSA, Trieste, Italy
85. SRC sistemske integracije d.o.o., Ljubljana, Slovenia
86. State College, Pennsylvania, USA
87. Stelar, Mede, Italy
88. The Faculty of Medicine of the University of Rijeka, Rijeka, Croatia
89. Institute of Physics, Zagreb, Croatia
90. TDK Electronics GmbH & Co OG, Deutschlandsberg, Austria
91. Technical University of Catalonia, Barcelona, Spain
92. TU Wien, Vienna, Austria
93. TELA merilni sistemi d.o.o., Ljubljana, Slovenia
94. The Geisel School of Medicine at Dartmouth, Hanover, USA
95. The Max Delbrück Center for Molecular Medicine in Berlin, Berlin, Germany
96. Tohoku University, Sendai, Japan
97. Tokyo University, Bunkjo, Tokyo, Japan
98. UNCOSS, Brussels, Belgium
99. Universita di Pisa, Dipartimento di Chimica e Chimica Industriale, Pisa, Italy
100. Universität Freiburg, Institut für Makromolekulare Chemie, Freiburg, Germany
101. Universität Mainz, Geowissenschaften, Mainz, Germany
102. Universität Regensburg, Regensburg, Germany
103. Université de la Méditerranée, Marseille, France
104. Université de Nice, Nice, France
105. Université de Picardie Jules Verne, Amiens, France
106. Université Paris Sud, Paris, France
107. University of Aveiro, Aveiro, Portugal
108. University of Bristol, Bristol, Great Britain
109. University of California at Irvine, Beckman Laster Institute and Medical Clinic, Irvine, California, USA
110. University of Duisburg, Duisburg, Germany
111. University of Durham, Durham, Great Britain
112. University of Innsbruck, Innsbruck, Austria
113. University of Leeds, Leeds, Great Britain
114. University of Linz, Institute of Chemistry, Department of Physical Chemistry & Linz Institute of Organic Solar Cells, Linz, Austria
115. University of Loughborough, Loughborough, Great Britain
116. University of Provence, Marseille, France
117. University of Tsukuba, Tsukuba, Ibaraki, Japan
118. University of Utah, Department of Physics, Salt Lake City, Utah, USA
119. University of Waterloo, Department of Physics, Waterloo, Ontario, Canada
120. University of Zürich, Zürich, Switzerland
121. University of Maribor, Maribor, Slovenia
122. University of Mons, Mons, Belgium
123. University of Munich and MPQ, Munich, Germany
124. University of Pavia, Pavia, Italy
125. University of North Carolina, Chapel Hill, USA
126. University of Wisconsin, Madison, USA
127. Wagenigen University, Laboratory of Biophysics, Wageningen, the Netherlands
128. Weizman Institute, Rehovot, Israel
129. Yonsei University, Seoul, South Korea
130. Blood Transfusion Centre of Slovenia, Ljubljana, Slovenia
131. Železarna Ravne, Ravne na Koroškem, Slovenia

ERC projects

1. H2020 - Cell-Lasers; Intracellular Lasers: Coupling of Optical Resonances with Biological Processes
   Asst. Prof. Matjaž Humar
   European Commission
2. H2020 - LOGOS; Light-Operated Logic Circuits from Photonic Soft-Matter
   Prof. Igor Muševič
   European Commission

Some outstanding publications in 2021

1. Schymura, Stefan, Drev, Sandra, Podlipec, Rok, Rijavec, Tomaž, Lapanje, Aleš, Štrok, Marko, et al. Dissolutionbased uptake of nanoparticles by freshwater shrimp: a dual-radiolabelling study of the fate of anthropogenic cerium in water organisms. Environmental science, Nano, ISSN 2051-8161, 11 pp., doi: 10.1039/d1en00264c.
2. Everts, J. C., Ravnik, M., Ionically charged topological defects in nematic fluids. *Phys. Rev. X,* 2021, **11**, 011054
3. Papič, M., Mur, U., Zuhail, K. P., Ravnik, M., Muševič, I., Humar, M., Topological liquid crystal superstructures as structured light lasers. *Proc. Natl. Acad. Sci. U.S.A.,* 2021, **118**, e2110839118
4. Peddireddy, K., Čopar, S., Le, V.K., Muševič, I., Bahr, C., Jampani, V.S.R., Self-shaping liquid crystal droplets by balancing bulk elasticity and interfacial tension. *Proc. Natl. Acad. Sci. U.S.A.,* 2021, **118**, e2011174118, 7
5. Pirker, L., Pogačnik Krajnc, A., Malec, J., Radulović, V., Gradišek, A., Jelen, A., Remškar, M., Mekjavić, I. B., Kovač, J., Mozetič, M., Snoj, L. Sterilization of polypropylene membranes of facepiece respirators by ionizing radiation. *J. Membr. Sci.* 2021, **619**, 118756
6. Del Pupo, S., Zupanič, E., et al. Tuning graphene doping by carbon monoxide intercalation at the Ni(111) interface. *Carbon*, 2021, **176**, 253.
7. Nasour, B., Vilfan, A., Golestanian, R., Minimum dissipation theorem for microswimmers. *Phys. Rev. Lett.*, 2021, **126**, 034503
8. Hickey, D., Vilfan, A., Golestanian, R., Ciliary chemosensitivity is enhanced by cilium geometry and motility. *eLife*, 2021, **10**, e66322
9. M. Klanjšek, „Singlets singled out“, *Nature Physics* **17**, 1081 (2021).
10. X. Chen, T. Yang, Q. Zhang, L. Q. Chen, **V. Bobnar**, C. Rahn, Q. M. Zhang, Topological structure enhanced nanostructure of high temperature polymer exhibiting more than ten times enhancement of dipolar response, *Nano Energy* **88**, 106226 (2021).
11. Y. Tanama et al., "Robust coherent spin centers from stable azafullerene radicals entrapped in cycloparaphenylene rings", *Nanoscale* **13**, 19946-19955 (2021).

Some outstanding publications in 2020

1. T. Arh, M. Gomilšek, P. Prelovšek, M. Pregelj, M. Klanjšek, A. Ozarowski, S. J. Clark, T. Lancaster, W. Sun, J.-X. Mi, A. Zorko. *Origin of magnetic ordering in a structurally perfect quantum kagome antiferromagnet*. Phys. Rev. Lett. **125** (2020) 027203.
2. P. Khuntia, M. Velazquez, Q. Barthélemy, F. Bert, E. Kermarrec, A. Legros, B. Bernu, L. Messio, A. Zorko, P. Mendels"Gapless ground state in the archetypal quantum kagome antiferromagnet ZnCu3(OH)6Cl2", Nat. Phys. 16, 469 (2020).
3. A. J. Hess, G. Poy, Jung-Shen B. Tai, S. Žumer, I. I. Smalyukh. *Control of light by topological solitons in soft chiral birefringent media.* Phys. Rev. X **10** (2020) 031042.
4. G. Poy, A. J. Hess, I. I. Smalyukh, S. Žumer. *Chirality-Enhanced Periodic Self-Focusing of Light in Soft Birefringent Media.* Phys. Rev. Lett. **125** (2020) 077801.
5. T. Strübing, A. Khosravanizadeh, A. Vilfan, E. Bodenschatz, R. Golestanian, I. Guido. *Wrinkling Instability in 3D Active Nematics*. Nano Lett. **20** (2020) 6281–6288.
6. J. Binysh, Ž. Kos, S. Čopar, M. Ravnik, G. P. Alexander. *Three-Dimensional Active Defect Loops.* Phys. Rev. Lett. **124** (2020) 088001.
7. K. Pal, A. Si, G. S. El-Sayyad, M. A. Elkodous, R. Kumar, A. I. El-Batal, S. Kralj, S. Thomas. *Cutting edge development on graphene derivatives modified by liquid crystal and CdS/TiO_2 hybrid matrix: optoelectronics and biotechnological aspects.* Critical Reviews in Solid State and Materials Sciences (2020).

8. H. Massana-Cid, A. Ortiz-Ambriz, A.Vilfan, P. Tierno. *Emergent collective colloidal currents generated via exchange dynamics in a broken dimer state*, Sci. Adv. **6** (2020) eaaz2257.
9. D. Richter, M. Marinčič, M. Humar. *Optical-resonance-assisted generation of super monodisperse microdroplets and microbeads with nanometer precision*. Lab Chip **20** (2020) 734–74.
10. P. Campinho, P. Lamperti, F. Boselli, A. Vilfan, J. Vermot. *Blood Flow Limits Endothelial Cell Extrusion in the Zebrafish Dorsal Aorta*. Cell Reports **31** (2020) 107505.
11. L. Pirker, B. Višić, S. D. Škapin, G. Dražić, J. Kovača, M. Remškar. *Multi-stoichiometric quasi-two-dimensional W_nO_{3n-1} tungsten oxides.* Nanoscale **12** (2020) 15102–15114.
12. A. Hassanien, B. Zhou, A. Kobayashi. *Spontaneous Antiferromagnetic Ordering in a Single Layer of $(BETS)_2GaCl_4$ Organic Superconductor.* Advanced Electronic Materials **6** (2020).
13. H. Kokot, B. Kokot, A. Sebastijanović, R. Podlipec, A. Krišelj, P. Čotar, M. Pušnik, P. Umek, S. Pajk, I. Urbančič, T. Koklič, J. Štrancar, et al. *Prediction of chronic inflammation for inhaled particles: the impact of material cycling and quarantining in the lung epithelium*. Adv. Mater. **32** (2020) 2003913.
14. A. Barbotin, I. Urbančič, S. Galiani, C. Eggeling, M. J. Booth. *Background reduction in sted-fcs using a bi-vortex phase mask*. ACS Photonics **7** (2020) 1742–1753.
15. A. Frawley, V. Wycisk, Y. Xiong, S. Galiani, E. Sezgin, I. Urbančič, A. Vargas Jentzsch, K. G. Leslie, C. Eggeling, H. L. Anderson. *Super-resolution resolft microscopy of lipid bilayers using a fluorophore-switch dyad.* Chem. Sci. **11** (2020) 8955–8960.

Awards and Appointments

1. Dr Luka Drinovec and Prof Griša Močnik, PhD: The Puh Award for outstanding achievements in the development of methods for measuring aerosol absorption, Ljubljana, The Government of the Republic of Slovenia
2. Asst. Prof. Anton Gradišek: Award for the best oral presentation at Ecobalt 2021 with the title "Particle Removal Efficiency of Face Masks During the Covid-19 Pandemic", Riga, Latvia (virtual)
3. Asst. Prof. Anton Gradišek: Team JSI vs COVID won 2nd place at XPRIZE Pandemic Response Challenge for finding best strategies against covid, Culver City, California, USA, XPRIZE Foundation (virtual)
4. Prof Miha Ravnik, PhD: The Blinc Award for physicists at the beginning of their career, Ljubljana, Faculty of Mathematics and Physics and Jožef Stefan Institute
5. Aljaž Kavčič, M.Sc.Phys.: The Prešeren Award for his master's thesis "Microscopy and sensing through scattering tissues using optical microresonators" (mentor Asst. Prof. Matjaž Humar), Ljubljana, University of Ljubljana
6. Prof Samo Kralj, PhD: Award for outstanding achievements in higher education, Ljubljana, The Council for Higher Education of the Republic of Slovenia
7. Asst. Prof. Uroš Tkalec: The Blinc Award for extraordinary one-time achievement in physics for a research in the field of imbalanced complex fluids that was published in *Nature Communications*, Ljubljana, Faculty of mathematics and physics and Jožef Stefan Institute

Organization of conferences, congresses and meetings

1. Alpine NMR Workshop, Bled, 16–20 September 2021

Patents granted

1. Janez Štrancar, Rok Podlipec, Iztok Urbančič, Zoran Arsov, Andrej Vrečko, Image-processing apparatus and image-processing method for detection of irregularities in tissue, EP3755994 (B1), European Patent Office, 26. 05. 2021.
2. Gregor Filipič, Kristina Eleršič, Darij Kreuh, Janez Kovač, Uroš Cvelbar, Miran Mozetič, A method of colouring titanium and titanium alloys, GB2530805 (B), Intellectual Property Office, 24. 11. 2021.
3. Vid Bobnar, Barbara Malič, Aleksander Matavž, A method for producing polymeric surface modification layers, SI25887 (A), Slovenian Intellectual Property Office, 31. 03. 2021.

INTERNATIONAL PROJECTS

1. **ERC H2020 - Cell-Lasers; Intracellular Lasers: Coupling of Optical Resonances with Biological Processes**
   Asst. Prof. Matjaž Humar
   European Commission
2. **ERC H2020 - LOGOS; Light-Operated Logic Circuits from Photonic Soft-Matter**
   Prof. Igor Muševič
   European Commission
3. Measurements of the Thickness of Chromium Deposits on a Glass Surface
   Prof. Miha Škarabot
   Pab Akrapović d. o. o.
4. COST CA16109; Chemical On-Line Composition and Source Apportionment of Fine Aerosol

Prof. Griša Močnik
Cost Office
5. COST CA16218; Nanoscale Coherent Hybrid Devices for Superconducting Quantum Technologies
Dr. Abdelrahim Ibrahim Hassanien
Cost Association Aisbl
6. COST CA16221; Quantum Technologies with Ultra-Cold Atoms
Dr. Peter Jeglič
Cost Association Aisbl
7. COST CA17121; Correlated Multimodal Imaging in Life Sciences
Prof. Janez Štrancar
Cost Association Aisbl
8. COST CA17139; European Topology Interdisciplinary Action
Prof. Slobodan Žumer
Cost Association Aisbl
9. COST CA16202; International Network to Encourage the Use of Monitoring and Forecasting Dust Products
Prof. Griša Močnik
Cost Association Aisbl
10. COST CA9108 - HiSCALE; High-Temperature SuperConductivity for AcceLerating the Energy Transition
Dr. Abdelrahim Ibrahim Hassanien
Cost Association Aisbl
11. BIO-OPT-COMM; A Living Optically-Communicating Neural Network
Asst. Prof. Matjaž Humar
Hfspo- International Human Frontier
12. H2020 - ENGIMA; Engineering of Nanostructures with Giant Magneto-Piezoelectric and Multicaloric Functionalities
Prof. Zdravko Kutnjak
European Commission
13. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
Prof. Maja Remškar
European Commission
14. H2020 - FoodTraNet; Advanced Research and Training Network in Food Quality, Safety and Security
Asst. Prof. Matjaž Humar
European Commission
15. H2020 - QMatCh; Towards Quantum States of Matter via Chemistry under Extreme Conditions
Prof. Denis Arčon
European Commission
16. Conservation of Cultural Heritage Indoors - The Case of Leonardo da Vinci's "Last Supper"
Prof. Griša Močnik
Slovenian Research Agency
17. Lipid Wrapped Nanoparticles and Activity of Factor Xa
Dr. Tilen Koklič
Slovenian Research Agency
18. Studies of Nanoporous Materials for Hydrogen Storage
Prof. Janez Dolinšek
Slovenian Research Agency
19. Magnetoresonance Study of Spin-Liquid Candidates
Prof. Andrej Zorko
Slovenian Research Agency
20. Advanced Organic and Inorganic Thin-Film Composites with Enhanced Dielectric and Electromechanical Response
Prof. Zdravko Kutnjak
Slovenian Research Agency
21. New Electronic States Emergent via Cross-Coupling between Magnetism and Electrical Conduction in Itinerant Antiferromagnetic Systems
Prof. Denis Arčon
Slovenian Research Agency
22. Hemoglobin-Based Nano-Spectral Non-Linear Imaging for Future Label-Free Medical Diagnostics
Dr. Rok Podlipec
Slovenian Research Agency
23. Impact of Fireworks on Air Pollution in Urban Environments
Asst. Prof. Anton Gradišek
Slovenian Research Agency
24. Investigation of Air Pollution with Nanoparticles Caused by Fireworks
Prof. Maja Remškar
Slovenian Research Agency
25. Positioning and Spatial Control of Magnetic Fullerides
Prof. Denis Arčon
Slovenian Research Agency
26. Tunable Memristive Switching in Carbon Nanotube Network for Neuromorphic Computing
Dr. Abdelrahim Ibrahim Hassanien
Slovenian Research Agency
27. Plasmon-Coupled Microcavities for Real-Time Molecular Sensing Inside Live Cells
Asst. Prof. Matjaž Humar
Slovenian Research Agency
28. Criticality Concept in Antiferroelectric Materials (CAMat)
Dr. Nikola Novak
Slovenian Research Agency

RESEARCH PROGRAMMES

1. Magnetic resonance and dielectric spectroscopy of „smart" new materials
Prof. Denis Arčon
2. Physics of Soft Matter, Surfaces and Nanostructures
Prof. Miha Ravnik
3. Experimental Biophysics of Complex Systems
Prof. Janez Štrancar

R & D GRANTS AND CONTRACTS

1. Electroporation-based treatments with new high-frequency electroporation pulses
Prof. Igor Serša
2. Reconstruction of electrical conductivity of tissues by means of magnetic resonance techniques
Prof. Igor Serša
3. Phase transitions towards coordination in multilayer networks
Dr. Uroš Jagodič
4. Development of building blocks for new European quantum communication network
Dr. Peter Jeglič
5. Development of high-performance piezoelectric coatings for self-powering of nonwovens used in e-mobility
Prof. Vid Bobnar
6. Probing spin states near the surface of quantum spin materials
Prof. Denis Arčon
7. Advanced soft nematocaloric materials
Asst. Prof. Brigita Rožič
8. Multicaloric cooling
Prof. Zdravko Kutnjak
9. Optimization of MRI techniques for assessment of thrombolytic treatment outcome
Prof. Igor Serša
10. Intracellular lasers: Coupling of optical resonances with biological processes
Asst. Prof. Matjaž Humar
11. Study of intracellular forces by deformable photonic droplets
Asst. Prof. Matjaž Humar
12. Electrocaloric elements for active cooling of electronic circuits
Prof. Vid Bobnar
13. Advanced inorganic and organic thin films with enhanced electrically-induced response
Prof. Vid Bobnar
14. Adverse outcome pathway leading to atherosclerosis
Dr. Tilen Koklič
15. Liquid-crystal microdroplet lasers for sensing inside live cells
Zuhail Kottoli Poyil
16. Stabilization and destabilisation of spin liquids by perturbations
Prof. Andrej Zorko
17. Physics of Majorana fermions in Kitaev magnets
Dr. Martin Klanjšek
18. Novel experimental approach for determination of quantum spin liquids
Prof. Andrej Zorko
19. Topological turbulence in confined chiral nematic fields
Prof. Miha Ravnik
20. Controllable broadband electromagnetic-radiation shielding
Dr. Matej Pregelj
21. Intelligent Content-Aware Nanospectroscopy (iCAN) of molecular events in nanoparticles-induced neurodegeneration
Asst. Prof. Iztok Urbančič
22. Self-assembly of Photon-Enabled Circuits using Topologically Reconfigurable Anisotropic Liquids
Venkata Subba Rao Jampani
23. Advanced optical magnetometry of vortices in unconventional superconductors
Prof. Denis Arčon
24. Diamond-assisted quantum processing of fullerene qubits
Prof. Denis Arčon
25. Coulombic subgap states in superconducting quantum devices
Prof. Denis Arčon
26. Spatial and temporal shaping of laser light for minimally invasive ophthalmic procedures
Prof. Janez Štrancar
27. Magnetic, electric and stress – field programming of shape response in polymer-dispersed liquid crystal elastomers – based actuators
Dr. Andraž Rešetič

28. Cryptographically secure random number generator
    Dr. Peter Jeglič
29. Cryptographically secure random number generator
    Dr. Peter Jeglič
    Urad Vlade Republike Slovenije za varovanje tajnih podatkov
30. CROSSING - Crossing Borders and Scales - An Interdisciplinary Approach
    Prof. Janez Štrancar
    Helmholtz-Zentrum Dresden-rossendorf E.v.
31. International Alpine NMR Workshop
    Prof. Igor Serša

NEW CONTRACTS

1. Detecion of Non-Anthropogenic Air Pollution project (DNAAP)
   Prof. Griša Močnik
   Aerosol d. o. o.
2. Magnetic, electric and stress - field programming of shape response in polymer-dispersed liquid crystal elastomers - based actuators
   Dr. Andraž Rešetič
   Kmz - Zalar Miran s.p.
3. Research and analysis of new molecular events and their causal connections in vitro
   Prof. Janez Štrancar
   Infinite d. o. o.

VISITORS FROM ABROAD

1. Dr Nych Andriy, National Academy of Sciences of Ukraine, Kyiv, Ukraine, 28 February–13 March 2021
2. Ivanović Arso, University of Montenegro, Podgorica, Montenegro, 1 March–20 April 2021
3. Dr Ryzhkova Anna, ASML B.V. Nederland, Amsterdam, The Netherlands, 30 May–19 June 2021
4. Dr Višić Bojana, Institute of Physics, Belgrade, Serbia, 31 May–1 August2021
5. Dr Nych Andriy and Dr Ognysta Uliana, National Academy of Sciences of Ukraine, Kyiv, Ukraine, 18 June–1 August 2021
6. Dr Kimouche Amina, University of Potsdam, Potsdam, Germany, 25 June–27 August 2021
7. Šenjug Pavla, Faculty of Science, Zagreb, Croatia, 30 August–3 September 2021
8. Dr Sebastiao Pedro, Instituto Superior Tecnico, Lisbon, Portugal, 11–18 September 2021
9. Dr Buganski Ireneusz, AGH Krakow, Krakow, Poland, 15 September–15 November 2021
10. Tanuma Yuri, CRNS, Nantes, France, 5–13 October 2021
11. Dr Lukyanchuk Igor and Dr Razumnaya Anna, Université de Picardie Jules Verne, LPMC, Amiens, France, 15 October–7 November 2021
12. Wojciechowski Adam, University of Krakow, Krakow, Poland, 16–20 October 2021
13. Dr Vinokour Valerii, Consortium for Advanced Science and Engineering, Chicago, USA, 29 October–3 November 2021
14. Dragojević Rajko and Šćepanović Stefan, University of Montenegro, Podgorica, Montenegro, 1 November–1 December 2021
15. Volkmann Jannis, Justus-Liebig University, Giessen, Germany, 14–20 November 2021
16. Dr Anyfantakis Emmanouil, University of Luxembourg, Luxembourg, Luxembourg, 14–20 November 2021
17. Dr Višić Bojana, Institute of Physics, Beograd, Serbia, 6–18 December 2021
18. Prof. El Marssi Mimoun, Université de Picardie Jules Verne, LPMC, Amiens, France, 10–12 December 2021

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18. Prof. Zdravko Kutnjak
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37. Dr. Herman Josef Petrus Van Midden
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50. *Dr. Zuhail Kottoli Poyil, on leave since 01.04.21*
51. Dr. Primož Koželj
52. *Dr. Mitja Krnel, on leave 07.04.21*
53. Dr. Marta Lavrič
54. Dr. Jože Luzar
55. Dr. Deepshika Malkar
56. Dr. Maruša Mur
57. Dr. Luka Pirker
58. Dr. Rok Podlipec
59. *Dr. Gregor Posnjak, on leave since 01.08.19*
60. Dr. Andraž Rešetič
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71. *Dr. Saša Harkai, left 01.12.21*
72. Anton Hromov, M. Sc.
73. *Nejc Janša, M. Sc., left 01.11.21*
74. Vida Jurečič, B. Sc.
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91. *Dr. Marion Antonia Van Midden, on leave since 01.09.21*
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98. Blaž Mencinger, M. Sc.
99. Jaka Močivnik, B. Sc.

Technical and administrative staff

100. Dražen Ivanov
101. Janez Jelenc, B. Sc.
102. Davorin Kotnik
103. Vesna Lopatič, B. Sc.
104. Silvano Mendizza
105. Peter Mihor
106. Janja Milivojević
107. Ana Sepe, B. Sc.
108. Marjetka Tršinar

Note:
* part-time JSI member

BIBLIOGRAPHY

Original Article

1. Neelakandan Marath Santhosh, Kush K. Updhyay, Petra Stražar, Gregor Filipič, Janez Zavašnik, André Mão de Ferro, Rui Pedro Silva, Elena Tatarova, Maria de Fátima Montemor, Uroš Cvelbar, "Advanced carbon-nickel sulfide hybrid nanostructures: extending the limits of battery-type electrodes for redox-based supercapacitor applications", *ACS applied materials & interfaces*, 2021, **13**, 17, 20559–20572.
2. Juan Casanova-Chafer, Polona Umek, Selene Acosta, Carla Bittencourt, Eduard Llobet, "Graphene loading with polypyrrole nanoparticles for trace-level detection of ammonia at room temperature", *ACS applied materials & interfaces*, 2021, **13**, 34, 40909–40921.
3. Petra Draksler, Urška Mikac, Peter Laggner, Amrit Paudel, Biljana Janković, "Polyethylene oxide matrix tablet swelling evolution: the impact of molecular weight and tablet composition", *Acta pharmaceutica*, 2021, **71**, 2, 215-243.
4. Andraž Bradeško, Lovro Fulanović, Marko Vrabelj, Aleksander Matavž, Mojca Otoničar, Jurij Koruza, Barbara Malič, Tadej Rojac, "Multifunctional cantilevers as working elements in solid-state cooling devices", *Actuators*, 2021, **10**, 3, 58.
5. Gregor Pirnat, Matjaž Humar, "Whispering gallery-mode microdroplet tensiometry", *Advanced photonics research*, 2021, **2**, 11, 2100129.
6. Lukas Link, Manisha Pathak, Franziska Jach, Primož Koželj, Alim H. Ormeci, Peter Höhn, Rainer Niewa, "The reduced nitridogermanates(III) $Ca_6[Ge_2N_6]$ and $Sr_6[Ge_2N_6]$ with Ge-Ge bonds", *Angewandte Chemie*, 2021, **60**, 14, 7691-7696.
7. Franziska Jach *et al.* (12 authors), "Tricyanidoferrates(-IV) and ruthenates(-IV) with non-innocent cyanido ligands", *Angewandte Chemie*, 2021, **60**, 29, 15879-15885.
8. Mao-Hua Zhang, Changhao Zhao, Lovro Fulanović, Jürgen Rödel, Nikola Novak, Alexander Schökel, Jurij Koruza, "Revealing the mechanism of electric-field-induced phase transition in antiferroelectric $NaNbO_3$ by in situ high-energy x-ray diffraction", *Applied physics letters*, 2021, **118**, 13, 132903.
9. Alexander Dubtsov, Sergey V. Pasechnik, Dina V. Shmeliova, Boris A. Umanskii, Samo Kralj, "Dual-frequency electrically driven nematic microstructures confined to biaxial porous polymer membranes", *Applied physics letters*, 2021, **119**, 22, 221903.
10. Oleg B. Baranov, Martin Košiček, Gregor Filipič, Uroš Cvelbar, "A deterministic approach to the thermal synthesis and growth of 1D metal oxide nanostructures", *Applied Surface Science*, 2021, **566**, 150619.
11. Maria Kezoudi *et al.* (25 authors), "The Unmanned Systems Research Laboratory (USRL): a new facility for UAV-based atmospheric observations", *Atmosphere*, 2021, **12**, 8, 1042.
12. Jesús Yus-Díez, Marina Ealo, Marco Pandolfi, Noemí Perez, Gloria Titos, Griša Močnik, Xavier Querol, Andrés Alastuey, "Aircraft vertical profiles during summertime regional and Saharan dust scenarios over the north-western Mediterranean basin: aerosol optical and physical properties", *Atmospheric chemistry and physics*, 2021, **21**, 1, 431-455.
13. Luca Ferrero, Asta Gregorič, Griša Močnik, Martin Rigler, Sergio Cogliati, Francesca Barnaba, Luca Di Liberto, Gian Paolo Gobbi, Niccolò Losi, Ezio Bolzacchini, "The impact of cloudiness and cloud type on the atmospheric heating rate of black and brown carbon in the Po Valley", *Atmospheric chemistry and physics*, 2021, **21**, 6, 4869-4897.
14. Anna Tobler *et al.* (15 authors), "Characterization of non-refractory (NR) PM_1 and source apportionment of organic aerosol in Kraków, Poland", *Atmospheric chemistry and physics*, 2021, **21**, 19, 14893-14906.
15. Vera Bernardoni *et al.* (14 authors), "Determination of Aethalometer multiple-scattering enhancement parameters and impact on source apportionment during the winter 2017/18 EMEP/ACTRIS/COLOSSAL campaign in Milan", *Atmospheric measurement techniques*, 2021, **14**, 4, 2919-2940.
16. Andrea Cuesta-Mosquera *et al.* (29 authors), "Intercomparison and characterization of 23 Aethalometers under laboratory and ambient air conditions: procedures and unit-to-unit variabilities", *Atmospheric measurement techniques*, 2021, **14**, 4, 3195-3216.
17. Jesús Yus-Díez *et al.* (13 authors), "Determination of the multiple-scattering correction factor and its cross-sensitivity to scattering and wavelength dependence for different AE33 Aethalometer filter tapes: a multi-instrumental approach", *Atmospheric measurement techniques*, 2021, **14**, 10, 6335-6355.
18. Rok Podlipec, Jaka Mur, Jaka Petelin, Janez Štrancar, Rok Petkovšek, "Method for controlled theranostics using a single tunable laser source", *Biomedical optics express*, 2021, **12**, 9, 5881-5893.
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