# DEPARTMENT OF SOLID STATE PHYSICS F-5

***Our research program is focused on the study of 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 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 new multifunctional materials, nanomaterials and biomaterials for new applications. An important part of the research program is devoted to the development of new experimental methods and techniques in the field of magnetic resonance, magnetic resonance imaging, fluorescence microspectroscopy, scanning tunnelling, electronic and atomic force microscopy, as well as dielectric relaxation spectroscopy and dynamic specific-heat measurements.***

Head:
***Prof. Igor Muševič***

The experimental techniques used are:

- One (1D) and two (2D) dimensional nuclear magnetic resonance (NMR) and relaxation, as well as quadrupole (NQR) resonance and relaxation,
- Multi-frequency NMR in superconducting magnets of 2T, 6T and 9T, as well as the dispersion of the spin–lattice relaxation time $T_1$ via field cycling,
- Nuclear double resonance and quadrupole double resonance such as $^{17}$O–H and $^{14}$N-H,
- Fast field cycling NMR relaxometry,
- Frequency-dependent electron paramagnetic resonance (EPR) and 1D and 2D pulsed EPR and relaxation
- MR imaging and micro-imaging
- Measurement of the electronic transport properties
- Magnetic measurements.
- Fluorescence microscopy and microspectroscopy
- Linear and non-linear dielectric spectroscopy in the range $10^{-2}$ Hz to $10^{9}$ Hz,
- Electron microscopy and scanning tunnelling microscopy,
- Atomic force microscopy and force spectroscopy,
- Dynamic specific heat measurements.

The research program of the Department of Solid State Physics at the Jožef Stefan Institute is performed in close collaboration with the Department of Physics at the Faculty of Mathematics and Physics of the University of Ljubljana, Institute of Mathematics, Physics and Mechanics and the J. Stefan International Postgraduate School. In 2015, the research was performed within three research programs:

- Magnetic resonance and 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 program group *Magnetic Resonance and Dielectric Spectroscopy of Smart New Materials* was focused on the study of physical phenomena in condensed matter at the atomic and molecular levels. The purpose of the investigations was to discover the basic laws of physics governing the behaviour of the investigated systems. The attained knowledge provides the key to an 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.

**The group discovered unconventional superconductivity in a molecular "Jahn-Teller" metal, synthesized the first hexagonal high-entropy alloy based on rare-earth elements and determined its complex magnetic phase diagram, studied new quantum effects in the magnetism of low-dimensional spin systems, the physical properties of nanostructures, materials with the giant electrocaloric and thermomechanical effect, and multiferroic and relaxor phases. The research included pharmaceutical and biological substances.**

In our research, we used the following 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,
- Measurements of electrical and thermal transport coefficients,
- Magnetic measurements.

The research program was performed in close collaboration with the Department of Physics at the Faculty of Mathematics and Physics of the University of Ljubljana, Institute of Mathematics, Physics and Mechanics, and the Jožef Stefan International Postgraduate School.

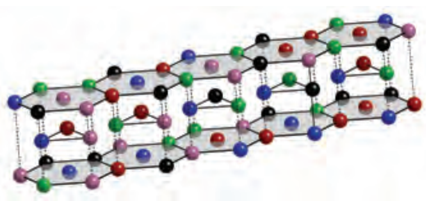

*Figure 1: Structure of the Ho-Dy-Y-Gd-Tb hexagonal high-entropy alloy.*

In 2015, members of the program group published 51 original scientific papers in international peer-reviewed scientific journals. Among these, one paper was published in *ACS Nano*, one in *Adv. Funct. Mater*., one in *Nature Commun*., one in *Phys. Rev. Lett*., one in *ACS Appl. Mater. & Interf*., two in *Sci. Rep*., two in *J. Phys. Chem. C*, one in *RSC Advances*, seven in *Phys. Rev. B* and eight in *Appl. Phys. Lett*. We also published one paper in *Science Advances*, which does not have an impact factor as yet.

The investigations were focused on the following research fields:

### 1. High-entropy alloys

In the publication "Complex magnetism of Ho-Dy-Y-Gd-Tb hexagonal high-entropy alloy" (J. Lužnik et al., *Phys. Rev. B* **92**, 224201 (2015)) we have reported on physical properties of the first hexagonal high-entropy alloy Ho-Dy-Y-Gd-Tb (Fig. 1). We have determined the magnetic phase diagram, which in a zero magnetic field shows a transition to a helical antiferromagnetic state at high temperatures, whereas at low temperatures a new kind of spin-glass phase appears. In a magnetic field, discontinuous metamagnetic phase transitions to exotic spin phases occur (Fig. 2).

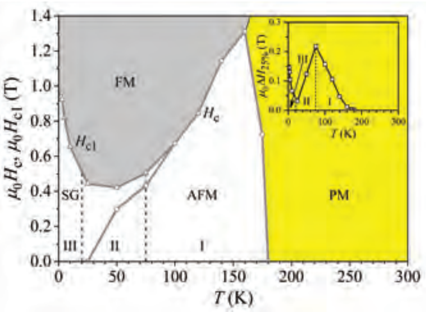


*Figure 2: Magnetic phase diagram of the Ho-Dy-Y-Gd-Tb hexagonal high-entropy alloy.*

### 2. Quantum magnetism

Matej Pregelj, Andrej Zorko in Denis Arčon have, in collaboration with partners from Switzerland, France and Japan, performed a comprehensive study of the β-$TeVO_4$ system. An impressive correspondence between a broad variety of experimental results, e.g., neutron diffraction and magnetization measurements in pulsed high-magnetic fields, with theory emphasizes the β-$TeVO_4$ compound as a model system of a frustrated spin chain with a rich phase diagram. The main result is the discovery of a magnetic stripe structure on the nano-scale, which appears at the transition between the spiral and collinear magnetic orders. In contrast to known strongly-correlated electron systems, here the stripes are stabilized in the absence of long-range magnetic interactions and are likely driven by weak frustrated interchain interactions. The presented model system thus allows a better understanding of the origin of the analogous nanometre-sized modulation in other systems, e.g., high-temperature superconductors. Their results were published in a paper by M. Pregelj et al., "Spin-stripe phase in a frustrated zigzag spin-1/2 chain", *Nat. Commun.* 6, 7255 (2015).

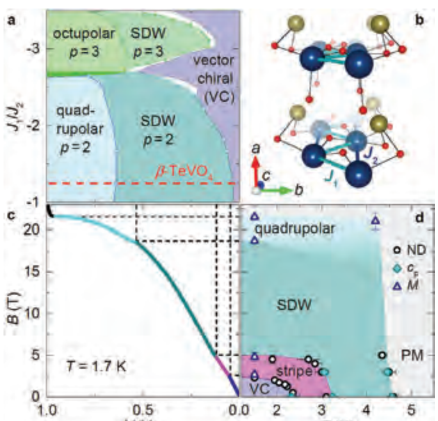


*Figure 3: Comparison of the theoretical and experimental phase diagrams. (a) Schematic phase diagram of the frustrated ferromagnetic spin-1/2 chain model as a function of J1/J2 and M/Msat. (b) The crystal structure of β-$TeVO_4$. Small, medium and large spheres denote O, Te and magnetic V ions, respectively. (c) Normalized magnetization measured in the magnetic field along the* a *axis. (d) The experimental magnetic phase diagram of β-$TeVO_4$, signifying the novel spin-stripe phase.*

Matej Pregelj, Andrej Zorko and Matjaž Gomilšek have in collaboration with partners from Switzerland, Germany and Moldova studied a mixed ferro/antiferromagnetic phase in the $Cu_3Bi(SeO_3)_2O_2Br$ system. Their results reveal the ability of metamagnetic materials to absorb the electromagnetic radiation across an extremely broad frequency range. The effect is controlled by the external magnetic field, which actuates a mixed ferro/antiferromagnetic phase, where the absorption in the $Cu_3Bi(SeO_3)_2O_2Br$ system extends over at least nine orders of frequency scale. Considering that artificial metamagnets (magnetic multilayers) allow for a direct control over the required magnetic field, a novel way of tuning the material's functional properties is imminent. Their work was published in the article by M. Pregelj et al., "Controllable broadband absorption in the mixed phase of metamagnets", *Adv. Func. Mat.* 25, 3634 (2015).

Andrej Zorko and Denis Arčon collaborated with partners from Slovenia, Greece and Switzerland in studying the inhomogeneous magnetic states of triangular spin lattices. Combining various local-probe experiments and numerical calculations they discovered crucial differences between isostructural α-$NaMnO_2$ and $CuMnO_2$ compounds and demonstrated that the ground state of the former compound is phase separated, while the latter is much more homogeneous. Such behaviour was believed to arise from the competition between the magnetic exchange and the elastic energies. Their discovery was published in the paper by A. Zorko et al., "Magnetic inhomogeneity on a triangular lattice: the magnetic-exchange versus the elastic energy and the role of disorder", *Sci. Rep.* **5**, 9272 (2015).

Martin Klanjšek, Tilen Knaflič and Denis Arčon, in collaboration with German colleagues, studied the structurally simple quantum antiferromagnet $CsO_2$ where the interplay of spin degrees of freedom with lattice vibrations and orbital ordering nevertheless leads to complex and interesting physics. Using magnetic resonance techniques, they showed that the system exhibits an exotic Tomonaga-Luttinger-liquid state at low temperatures where orbital ordering takes place. Sizeable lattice vibrations at higher temperatures lead to the huge temperature dependence of the exchange interaction, providing the first clear demonstration of this effect, predicted three decades ago. The work has been published in the papers M. Klanjšek et al., "Phonon-Modulated Magnetic Interactions and Spin Tomonaga-Luttinger Liquid in the *p*-Orbital Antiferromagnet $CsO_2$", *Phys. Rev. Lett.* **115**, 057205 (2015), and T. Knaflič et al., "One-dimensional quantum antiferromagnetism in the *p*-orbital $CsO_2$ compound revealed by electron paramagnetic resonance", *Phys. Rev. B* **91**, 174419 (2015).

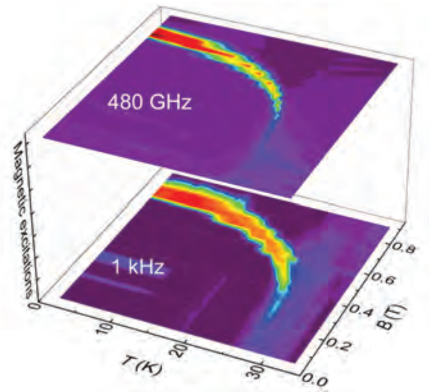

*Figure 4: The imaginary part of the ac susceptibility, χ″ (bottom panel), and electron magnetic resonance at 480 GHz (top panel) plotted as a function of field and temperature. The red and the violet regions correspond to the highest and lowest absorption intensities, respectively.*

Martin Klanjšek, in collaboration with French colleagues, studied the system of antiferromagnetic spin chains $BaCo_2V_2O_8$, which exhibits a very interesting phase diagram when a magnetic field is applied along the magnetic exchange easy axis. Because of the competition between the two types of spin fluctuations, present when the spin chains realize a Tomonaga-Luttinger-liquid state at low temperatures, two magnetically ordered phases are expected. A surprising observation of three magnetic phases leads to the conclusion of a giant magnetic field dependence of the exchange coupling. The work was published in the papers M. Klanjšek et al., "Giant magnetic field dependence of the coupling between spin chains in $BaCo_2V_2O_8$", *Phys. Rev. B* **92**, 060408(R) (2015), and B. Grenier et al., "Neutron diffraction investigation of the *H-T* phase diagram above the longitudinal incommensurate phase of $BaCo_2V_2O_8$", *Phys. Rev. B* **92**, 134416 (2015).

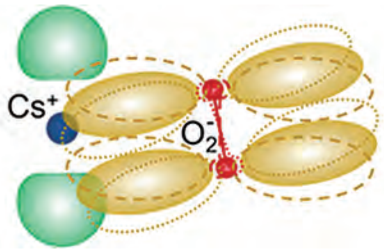

*Figure 5: Schematic of the varying overlap of Cs $p_z$ orbitals and $O_2^-$ π* orbitals in the process of $O_2^-$ librations, which leads to the modulation of the exchange interaction.*

### 3. Diluted magnetic systems

Andrej Zorko, Matej Pregelj and Matjaž Gomilšek collaborated with partners from Slovenia, Croatia and Great Britain in investigations of high-temperature ferromagnetism in the Fe-doped 6H-$BaTiO_3$. Although in this material the high-temperature ferromagnetism was previously widely accepted as an intrinsic property, they proved this conjecture to be wrong. A combination of bulk magnetization and complementary in-depth local-probe electron spin resonance and muon spin relaxation measurements clearly revealed that multiple magnetic instabilities occurring in this material coincide with the electronic instabilities of the Fe-doped 3C-$BaTiO_3$ pseudocubic polymorph. They thus demonstrated that the intricate magnetism of the hexagonal phase is not intrinsic, but is rather due to sparse strain-induced pseudocubic regions. Their discovery was published in the paper by A. Zorko et al., "Strain-Induced Extrinsic High-Temperature Ferromagnetism in the Fe-Doped Hexagonal Barium Titanate", *Sci. Rep.* **5**, 7703 (2015).

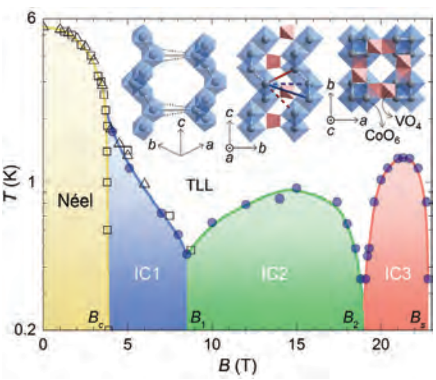

*Figure 6: Phase diagram of the system of antiferromagnetic spin chains $BaCo_2V_2O_8$ in a magnetic field applied along the magnetic exchange easy axis.*

### 4. Unconventional superconductivity

Denis Arčon, Peter Jeglič and Anton Potočnik contributed some crucial experimental evidence for a new type of metallic state of matter, discovered by an international team of researchers from England, Slovenia, Japan and Hungary when studying a superconductor made from $C_{60}$ molecules. The team found the new state after changing the distance between the neighbouring $C_{60}$ molecules by doping the parent $Cs_3C_{60}$ compound with rubidium. The study reveals that the material has a remarkably rich combination of insulating, magnetic, metallic and superconducting phases – including the hitherto unknown state, which the researchers have dubbed a "Jahn–Teller metal". These studies are extremely important for our understanding of how superconductivity evolves in cases when several degrees of freedom are intertwined – in our case these are electronic, spin and molecular degrees of freedom. The article has been published in *Science Advances* (Zadik et al., *Sci. Adv.* **1**, e1500059 (2015)), a new research journal of *AAAS (Science)*, and has been picked up by several news

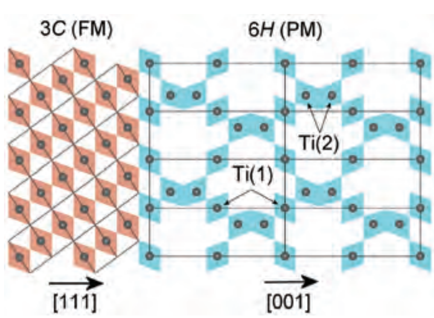

*Figure 7: Schematic interface of the two crystallographic phases in $BaTiO_3$, the pseudocubic (3C) and the hexagonal (6H) crystallographic polymorphs. High-temperature ferromagnetism (FM) is ascribed to sparse regions of the 3C phase, while the majority 6H phase remains paramagnetic (PM).*

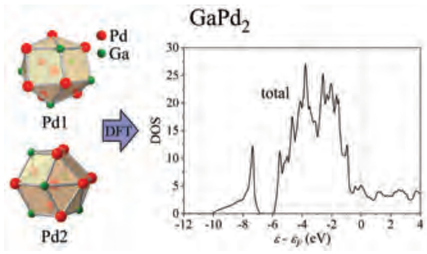

*Figure 8: Structure of GaPd2 and the electronic density of states.*

outlets, including physicsworld.com. Moreover, the article was ranked as the 6th most viewed article in this journal in 2015.

Peter Jeglič, Martin Klanjšek and Denis Arčon studied a hyper-interlayer-expanded FeSe-based material with a very high superconducting critical temperature $T_c$ = 45 K. The study, a joint investigation between several groups from Japan and Slovenia, revealed a complete decoupling of the interlayer units from the conduction electrons in FeSe layers, the non-negligible concentration of Fe impurities present in the insulating interlayer space, and most importantly, the absence of the electronic nematic order and spin fluctuations down to $T_c$. Despite these findings, the results imply that the Cooper pairing is mediated by spin fluctuations. The study has been published in M. Majcen Hrovat et al., *Phys. Rev. B* 92, 094513 (2015).

5. Complex metallic alloys

M. Klanjšek, M. Krnel, S. Vrtnik, P. Koželj, A. Jelen and J. Dolinšek studied an interesting intermetallic compound $GaPd_2$ using a combination of thermal, electrical and magnetic property measurements, and nuclear magnetic resonance. The compound, which represents a highly selective catalytic material for the semi-hydrogenation of acetylene, was studied in the single-crystal morphology as well as in the nanoparticle morphology, which is used in catalysis. They found that the electronic properties of the compound are not much different in both morphologies, while the behaviour of the compound is very similar to the behaviour of the related compound GaPd. The work is published in the paper by M. Wencka et al., "Physical properties of the $GaPd_2$ intermetallic catalyst in bulk and nanoparticle morphology", *Intermetallics* 67, 35 (2015).

6. Study of nanostructured materials and materials with a large electrocaloric effect and its application in a solid-state cooling device

Using direct measurements we demonstrated the existence of the positive and negative electrocaloric effects in antiferroelectric material doped with barium. With indirect and direct experiments, we showed a large electrocaloric effect in lead-free ferroelectric relaxors. First, we made, in cooperation with the Engineering Faculty, a working prototype of an electrocaloric solid-state cooling device that is based on ceramic cooling elements and does not use cooling gases. We were invited to write an article about the electrocaloric effect in the distinguished Wiley Encyclopedia of Electrical and Electronics Engineering. The above results have been published in 11 articles in international scientific journals (e.g. U. Plaznik et al., *Appl. Phys. Lett.*, 2015, vol. 106, pp. 1-4; B. Asbani et al., *Appl. Phys. Lett*, 2015, vol. 106, pp. 042902-1-042902-4; J. Korzua et al., *Appl. Phys. Lett.*, 2015, vol. 106, pp. 202905-1-202905-4) and an article in an encyclopaedia (Z. Kutnjak et al.: "Electrocaloric effect : theory, measurements, and applications. *Wiley Encyclopedia of Electrical and Electronics Engineering*." 2015, pp. 1-19). Recently published works on electrocalorics and the stabilization of the TGB and blue phases have been cited more than 100 times in 2015 alone.

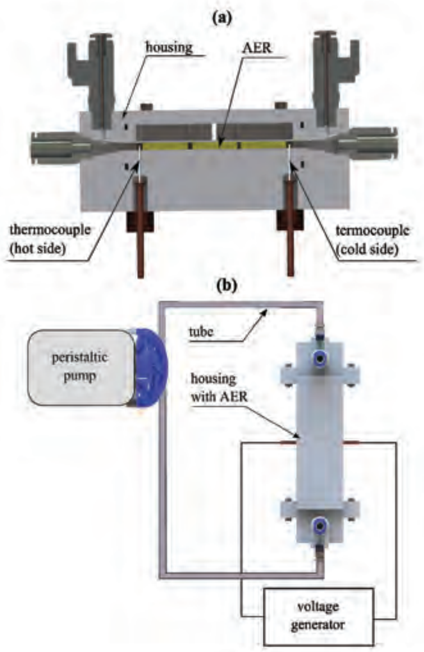

*Figure 9: Prototype of electrocaloric cooling device based on the regeneration principle. The regenerator block is presented in (a), here AER denotes the ceramic electrocaloric elements. The complete device is shown in (b).*

Large electrocaloric effect in grain-size-engineered ceramics

We have shown that a substantial enhancement of the electrocaloric (EC) effect can be achieved with a properly engineered ceramic microstructure. In particular, a significant impact of the grain size on the EC effect in the $0.9Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.1PbTiO_3$ system was demonstrated. The single-phase perovskite ceramics with grain sizes ranging from 2.8 to 9.4 μm were prepared. The largest EC coefficient was obtained for ceramics with 5.8 μm grains, as a consequence of its large saturation polarization. The EC response is limited by the breakdown strength of the material, which is higher than 160 kV/cm for the fine-grained ceramics. For the material with a 98 % relative density and 3.6-μm grains, a large EC temperature change of 3.45 K was achieved, which is the highest reported value so far for Pb-based perovskites and is comparable to best results obtained by multi-critical-point enhancement. The findings were published in a paper by M. Vrabelj et al., "Large electrocaloric effect in grain-size-engineered $0.9Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.1PbTiO_3$ ceramics", *J. Eur. Ceram. Soc.* 36, 75 (2016).

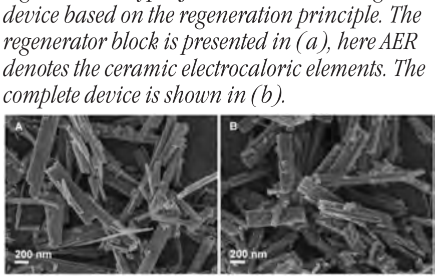

*Figure 10: SEM images of $TiO_2$ nanoribbons transformed from protonated titanate nanoribbons with calcination in air (a) and hydrothermal treatment in water (b).*

7. Synthesis and physical properties of nanomaterials

Melita Rutar, Matej Pregelj and Polona Umek have together with partners from the Slovenian National Building and Engineering Institute, the University of Ljubljana and the University of Mons studied the impact of reaction conditions on the photocatalytic properties of $TiO_2$ nanoribbons (NRs). The $TiO_2$ NRs were synthetized from protonated titanate nanoribbons (HTiNRs) under different reaction conditions in order to improve the photocatalytic activity of the $TiO_2$ NRs. The transformation from HTiNRs to $TiO_2$ NRs was performed with calcination in air or a reductive $NH_3$ atmosphere, and with hydrothermal treatment in water or $NH_3$(aq). The key factors that influence the material's photoactivity are the crystal phase, the degree of crystallinity, the specific surface area and the width of the bandgap. A calcination in the air provided anatase NRs with the highest crystallinity. A transformation under hydrothermal conditions resulted in an increase of the specific surface area of the material, and reactions in $NH_3$ media (atmosphere or aqueous solution) led to N-doping. The photocatalytic activity of the products was evaluated from the photo-oxidation of the isopropanol to acetone. The best results were obtained from the anatase NRs that were firstly hydrothermally transformed from HTi NRs in water and were additionally calcinated in air. With this we synthetized anatase NRs with an increased specific surface area and high crystallinity. N-doping led to light absorption also in the visible region; however, the photocatalytic activity was supressed as the doping sites acted also as recombination sites. The work was published in a paper by M. Rutar et al., *Belstein J. Nanotechnol.,* 6, (2015), 831.

Melita Sluban, Polona Umek and Denis Arčon performed, in collaboration with colleagues from the JSI and partners from Belgium, France and Germany a synthesis study of titanium oxyntride nanostructures. In this study the authors demonstrated that the slow anion diffusion in anion exchange reactions can be efficiently used to tune the disorder strength and the related electronic properties of nanoparticles. This paradigm was applied to the high-temperature formation of titanium oxynitride nanoribbons, Ti(O,N), transformed from hydrogen titanate NRs in an ammonia atmosphere. The nitrogen content, which determines the chemical disorder through a random O/N occupancy and ion vacancies in the Ti(O,N) composition, increases with the reaction time. The presence of disorder has important effects on the resistivity of Ti(O,N) NRs. Atypically for metals, the resistivity increases with decreasing temperature due to the weak localization effects. From this state superconductivity develops below considerably or completely suppressed critical temperatures, depending on the disorder strength. Their results were published in a paper by M. Sluban et al., "Controlling disorder and superconductivity in titanium oxynitride nanoribbons with anion exchange", *ACS nano,* 9 (2015), 10133.

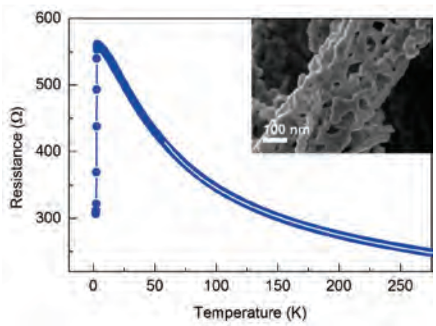


*Figure 11: Temperature dependence of resistivity of superconducting titan oxynitride nanoribbons. Inset: SEM image shows a mesoporous structure of a titan oxynitride nanoribbon.*

With partners from Spain, Belgium and Germany, Polona Umek collaborated in research on a gas-sensitive hybrid material consisting of $Cu_2O$ nanoparticle-decorated $WO_3$ nanoneedles. The material was successfully grown for the first time in a single step via aerosol-assisted chemical vapour deposition. Morphological, structural, and composition analyses show that our method is effective for growing single-crystalline, n-type $WO_3$ nanoneedles decorated with p-type $Cu_2O$ nanoparticles at moderate temperatures (i.e., 380 °C), with cost effectiveness and short fabrication times, directly onto micro-hot-plate transducer arrays with a view to obtaining gas sensors. The gas-sensing studies performed show that this hybrid nanomaterial has excellent sensitivity and selectivity to hydrogen sulphide (7-fold increase in response compared with that of pristine $WO_3$ nanoneedles) and a low detection limit (below 300 ppb of $H_2S$), together with unprecedented fast response times (2 s) and high immunity to changes in the background humidity. The results were published in the paper by F. E. Annanouch et al., "Aerosol assisted CVD grown $WO_3$ nanoneedles decorated with copper oxide nanoparticles for the selective and humidity resilient detection of $H_2S$", *ACS applied materials & interfaces,* 7(2015), 6842.

### 8. Hydrogen dynamics in $Zr_{69.5}Cu_{12}Ni_{11}Al_{7.5}$ hydrogen storage alloy

We studied the hydrogen dynamics in a partially quasicrystalline hydrogen/storage alloy $Zr_{69.5}Cu_{12}Ni_{11}Al_{7.5}$ by a combination of fast-field-cycling nuclear magnetic relaxometry and diffusometry in a static fringe field. We demonstrate that proton spin–lattice relaxation cannot be explained using a single activation energy for the proton hopping between the interstitial sites. Instead, the behaviour is better explained using a Gaussian distribution of activation energies, with the average value closely matching the one obtained in independent direct diffusion measurements. Knowing the diffusion constant and the correlation times for proton jumps, we can directly estimate the average jump length. The findings were published in a paper by A. Gradišek and Apih, T, "Hydrogen dynamics in partially quasicrystalline $Zr_{69.5}Cu_{(12)}Ni_{(11)}Al_{(7.5)}$: fast field cycling relaxometry study", *The Journal of Physical Chemistry C*, vol. 119, no. 19, 10677-10681.

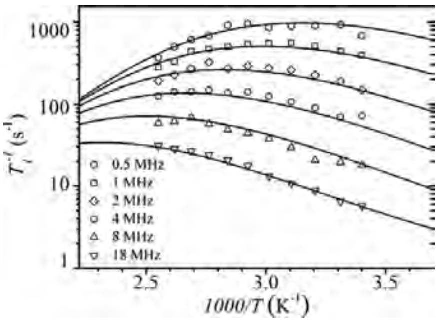


*Figure 12: Proton spin-lattice relaxation dispersion in a $Zr_{69.5}Cu_{12}Ni_{11}Al_{7.5}$ quasicrystal.*

### 9. Quantitative Analysis of Hydration Using $^{14}N$ Nuclear Quadrupole Resonance

In the paper by A. Gregorovič, *Anal. Chem.* 87, 6912-6918, 2015, we present the use of $^{14}N$ NQR spectroscopy to quantitatively analyse the hydration of a model compound 5-aminotetrazole. This method utilizes the fact that by hydrating a molecular crystal we shift the characteristic $^{14}N$ NQR frequency by a large amount (~ 100 kHz) so that the anhydrate and the hydrate resonances are easily distinguished in the spectrum of a partially hydrated compound. Thus, the spectrum can be used to determine the integral intensities of the two peaks that are directly proportional to the amounts of each phase. $^{14}N$ NQR has several advantages over other techniques used to study hydration (like

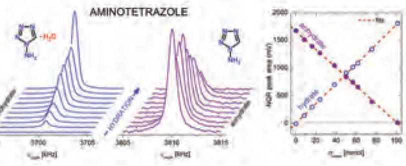


*Figure 13: (left, centre) The $^{14}N$ NQR spectrum of aminotetrazole and its hydrate for several samples with a different degree of hydration. (right) Correlation between the water amount in the samples obtained with $^{14}N$ NQR and by heating to constant mass.*

XRD, NIR, $^{35}$Cl NQR, etc.). First, the $^{14}$N NQR spectrum is very simple, and second, a single-point calibration is also sufficient. On the other hand, the method's great disadvantage is low sensitivity, which limits the use of the technique to large samples. Nevertheless, we have achieved accuracies <1% for samples whose temperature was carefully stabilized by extending the experimental time.

### 10. Polymer-dispersed liquid-crystalline elastomers

We have developed polymer-dispersed liquid-crystal elastomers (PDLCE) with a composite structure of aligned liquid-crystal elastomer (LCE) microparticles embedded in a conventional elastomer matrix. These composites exhibit an increased thermomechanical response, in analogy to the increase of the electric conductivity in polymers doped with conductive particles. We have demonstrated that, by aligning the LCE microparticles in the magnetic field during the polymerization phase, structures with arbitrary spatial configurations of thermomechanical anisotropy can be prepared, which determine the mechanical deformation mode during thermal actuation of the specimen. Based on our discoveries, we applied for the patent "Polymer dispersed liquid crystal elastomers (PDLCE)", A. Rešetič et al., PCT/EP2015/055527, publication number WO2015/140149 A1, publication date 24 September 2015.

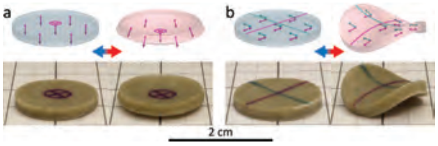


*Figure 14: Thermal actuation of PDLCE samples with a double-layer configuration of LCE microparticles: a) out-of-plane alignment in the bottom layer, no alignment in the top layer, resulting in a concave deformation and b) in-plane alignment with crossed directors, resulting in a saddle-like deformation of the specimen on heating.*

After the linear and particularly nonlinear dielectric experiments revealed that ferroelectric and relaxor states coexist in blends of relaxor P(VDF-TrFE-CFE) terpolymer and ferroelectric P(VDF-TrFE) copolymer (such a coexistence strongly enhances the electrocaloric response of a system), differential scanning calorimetry confirmed that both components form separate crystalline phases. Moreover, calorimetric experiments revealed the influence of blending on the crystallinity and melting points of both components. Finally, the relative crystallinity data, obtained from the normalized enthalpy changes during melting, appropriately explain the variation of the dielectric constant in developed blends. The findings were published in a paper by G. Casar et al., "Impact of structural changes on dielectric and thermal properties of vinylidene fluoride-trifluoroethylene-based terpolymer/copolymer blends", *Physica B: Condens. Matter* 461, 5 (2015).

### 11. Unusual structural-disorder stability of mechanochemically derived $Pb(Sc_{0.5}Nb_{0.5})O_3$

Relaxors are of great interest for a wide range of applications as they exhibit high dielectric and electromechanical responses over broad temperature ranges as well as a large electrocaloric effect. In collaboration with the Electronic Ceramics Dept., the Institute of Chemistry, and researchers from France, Austria, and the USA, we have demonstrated the important effect of processing on the B-site ordering in well-known relaxor $Pb(Sc_{0.5}Nb_{0.5})O_3$ ceramics. In contradiction to previous observations on ceramics prepared from solid-state synthesis powders, which show a distinctive B-site cation ordering when annealed below 1200 °C, in mechanochemically derived ceramics sintered much below this temperature, no such ordering was observed, regardless of the thermal post-annealing conditions. Accordingly, atomic-scale transmission electron microscopy revealed nanometre-sized B-site ordered regions in mechanochemically derived ceramics, in contrast to the larger regions extending through the whole grains in a solid-state-derived system. The results of the work have established an understanding of the relationship between the synthesis method, the B-site cation ordering in the relaxor ceramics, and its functional properties, particularly the dielectric response and electrical polarization. The findings were published in a paper by H. Uršič et al., "Unusual structural-disorder stability of mechanochemically derived- $Pb(Sc_{0.5}Nb_{0.5})O_3$", *J. Mater. Chem. C* 3, 10309 (2015).

### 12. Pharmaceutical substances

$^{14}$N NQR represents a useful tool to characterize pharmaceutical substances and the method of their preparation. In combination with quantum chemical calculations the electronic structure of these molecules and the properties of the functional groups can be determined. These discoveries were published in a paper by J. N. Latosińska et al. "Unusual case of desmotropy. Combined spectroscopy ($^{1}$H-$^{14}$N NQDR) and quantum chemistry (periodic hybrid DFT/QTAIM and Hirshfeld surface-based) study of solid dacarbazine (anti-neoplastic)", *Solid State Nuclear Magnetic Resonance* 68-69, 13–24 (2015).

The antineoplastic chemo-therapeutic drug 5-(3,3-dimethyl-1-triazenyl)imidazole-4-carboxamide (Dacarbazine, DTIC) has been studied experimentally in the solid state by $^{1}$H-$^{14}$N NQDR double resonance at 295K and theoretically by the Density Functional Theory (DFT)/ Quantum Theory of Atoms in Molecules (QTAIM) and Hirshfeld surfaces analysis. Only one set of eighteen resonance frequencies was found in the experiment. This indicates the presence of six non-equivalent nitrogen sites: $-N(CH_3)$, $-NH_2$, -NH- and three –N= (of which one is a ring, two are from triazene) in the DTIC molecule. This contradicts the X-ray data, which revealed the multiplication of nitrogen sites due to unusual desmotropism. The averaging of the NQR frequencies caused by the fast NQR time-scale exchange of protons in a double-well potential combined with the oscillations of twisted supramolecular synthons was proposed as a potential mechanism responsible for this apparent contradiction. An effective improvement in the quality of the spectrum reproduction was achieved when the calculations were performed assuming the periodic boundary conditions, BLYP functional, the DNP basis set and taking the 3×3×3 k-point separation. The ordering of the nitrogen sites according to the increasing quadrupole coupling constant (QCC):N(3)<N (2)<N(6)<N(1)<N(4)<N(5) reflects the metabolic pathway of DTIC. Two sites N(5) and N(4) with the highest QCC are responsible for the first step – conversion to MTIC (5-[3-methyl-triazen-1-yl]-imidazole-4-carboxamide) required for effective processes of binding dacarbazine to DNA (demethylation of N(5)), and the second step – fast conversion of MTIC to 5-amino-1H-imidazole-4-carboxamide (AIC; remove – N(4)-N(5)$HCH_3$). N(5) does not participate in any, while N(4) participates in a weak C(2)H···N(4) interaction that can be readily broken. The four remaining nitrogen atoms N(1), N(2), N(3) and N (6) participate in strong intermolecular N(1)H···N(2) and intramolecular N(3)–H···N(6) bonds, which stiffen the crystalline structure. These findings were published in a paper by J. N. Latosińska et al., "Impact of structural differences in carcinopreventive agents indole-3-carbinol and 3,3'-diindolylmethane on biological activity. An X-ray, $^{1}H$–$^{14}N$ NQDR, $^{13}C$ CP/MAS NMR, and periodic hybrid DFT study", *European Journal of Pharmaceutical Sciences* 77, 141–153 (2015).

Three experimental techniques $^{1}H$–$^{14}N$ NQDR, $^{13}C$ CP/MAS NMR and X-ray and Density Functional Theory (GGA/BLYP with PBC) and Hirshfeld surfaces were applied for the structure–activity-oriented studies of two phyto-antioxidants and anticarcinogens: indole-3-carbinol, I3C, and 3,30-diindolylmethane, DIM, (its bioactive metabolite). One set of $^{14}N$ NQR frequencies for DIM and I3C was recorded. The multiplicity of the NQR lines reveal the high symmetry (chemical and physical equivalence) of both the methyl indazole rings of the DIM. Carbonyl $^{13}C$ CSA tensor components were calculated from the $^{13}C$ CP/MAS solid-state NMR spectrum of I3C recorded under fast and slow spinning. At room temperature the crystal structure of I3C is orthorhombic: space group Pca21, Z = 4, a = 5.78922(16), b = 15.6434(7) and c = 8.4405(2) A. The I3C molecules are aggregated into ribbons stacked along [001]. The oxygen atoms are disordered between the two sites of different occupancy factors. It implies that the crystal is built of about 70% trans and 30% gauche conformers, and apart from the weak O-H---O hydrogen bonds (O---O = 3.106 A) the formation of alternative O'-H---O bonds (O'---O = 2.785 A) is possible within the 1D ribbons. The adjacent ribbons are further stabilised by O'-H---O bonds (O'---O = 2.951 A). The analysis of spectra and intermolecular interactions pattern using experimental techniques was supported by solid (periodic) DFT calculations. The knowledge of the topology and competition of the interactions in the crystalline state shed some light on the preferred conformations of -$CH_2OH$ in I3C and the steric hindrance of methyl indole rings in DIM. A comparison of the local environment in the gas phase and the solid permitted drawing some conclusions on the nature of the interactions required for effective processes of recognition and binding for a given anticarcinogen to the protein or nucleic acid.

## *II. Research programme "Physics of Soft Matter, Surfaces, and Nanostructures"*

The investigations of the research program "Physics of Soft Matter, Surfaces, and Nanostructures" are focused on novel complex soft-matter systems and surfaces with specific functional properties. We investigated in particular liquid-crystalline elastomers and dendrimers as novel multifunctional materials, nematic colloids, molecular motors, soft-matter photonic crystals and novel synthetic or self-assembled micro- and nano-structures. The aim of the program 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. In order 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 the possible electro-optic and medical applications.

**The group explored topological defects and their topological charge as well as the topology of knots and links in liquid crystals. We studied the ultrafast optical response of soft matter and molecular motors. We explored new types of nanowires and the surfaces of superconductors at the single-atom level.**

### Light-controlled topological charge in a nematic liquid crystal

Like the electric charges in electromagnetism, topological charges are sources of a physical field, which are observable in superconductors, superfluids, cold atoms, ferromagnetic materials and even light. Whereas in these systems the topological charge is difficult to create and control, it is an easy task to create and manipulate topological charges in liquid crystals. Here, the topological charge is attributed to topological defects, which are singularities of the orientational field describing the liquid-crystal alignment. In a paper entitled "Light-controlled topological charge in a nematic liquid crystal", published by M. Nikkhou et al. in *Nat. Phys.* 11, 183 (2015), the authors demonstrated full control over the creation, manipulation and analysis of topological defects that are pinned

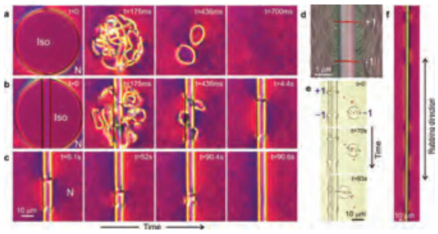

*Figure 15: Creation and annihilation of topological charges on a fibre. (a) The NLC is heated into the isotropic phase by the strong light of the laser tweezers, thus creating an isotropic island (Iso). At t = 0 the light is switched off and the NLC is quenched into the nematic phase (N). The dense tangle of defects annihilates in less than a second. (b) The NLC is quenched from the isotropic island surrounding a fibre. A pair of defects is created, each carrying an opposite topological charge. (c) If let free, the pair annihilates into the vacuum. (d) LdG simulation of the Saturn ring and the Saturn anti-ring with opposite charges and windings. (e) The sign of the charge is tested using the repulsive force between like topological charges. (f) An arbitrary number of ring–anti-ring pairs can be created on a fibre. Images (a–c, f) were taken between crossed polarisers and the red plate that shows the average molecular orientation in different colours.*

to a microfibre immersed in a nematic liquid crystal. Using the laser tweezers, they created pairs of defects carrying opposite topological charges, which were manipulated and moved by the force of the laser tweezers. They observed long-lived pairs of oppositely charged rings or points that either attracted and annihilated, or formed long-lived, charge-neutral loops made of two segments with a fractional topological charge (Figure 15).

In a follow-up publication entitled "Topological binding and elastic interactions of microspheres and fibres in a nematic liquid crystal" published by Nikkhou, Škarabot and Muševič in *Eur. Phys. J.* E 38, 15023-6 (2015), the authors present an analysis of the topological binding of microspheres to a fibre in a nematic liquid crystal. They observed the entanglement and topological charge interaction between the various types of defects on the ring and microspheres and observed strong pair-interaction forces. These forces were explained with a simple topological rule: like topological charges repel each other and opposite topological charges attract. This article was highlighted in the *European Physical Journal* published in September 2015 and the cover image of that issue was taken from this article.

### Topological defect transformation across the nematic-to-smectic-A phase transition

We studied the topological defects associated with small microspheres with perpendicular surface anchoring of the liquid-crystal molecules across the nematic-to-smectic-A phase transitions. Because the topological defects are regions of strong electric deformation, it is expected that any variation in the elastic constants should strongly influence the defect structure. We observed that a nematic hyperbolic hedgehog defect, which accompanies a microsphere in a nematic liquid crystal, is gradually transformed into a focal conic line in the smectic-A phase.

This defect transformation has a strong influence on the structural force between a pair or several colloidal particles in the nematic and smectic-A phase. The pre-transitional behaviour of the defect is well supported by the Landau-de Gennes numerical modelling published in *Physical Review E* 92, 052501(2015) by Zuhail et al. The transformation of the Saturn ring defects associated with spherical microparticles across the nematic-to-smectic-A phase transition were studied by Zuhail et al. and published in Physical Review E 92, 052501(2015). It was observed that the director structure around each microparticle changes rapidly with temperature and has a strong impact on the pair-interaction colloidal forces. The onset of the smectic order influences not only the interparticle separation but also the angular dependence. As a consequence, 2D colloidal crystals are not stable in the smectic-A phase as the crystal dissolves irreversibly across the nematic–smectic-A transition.

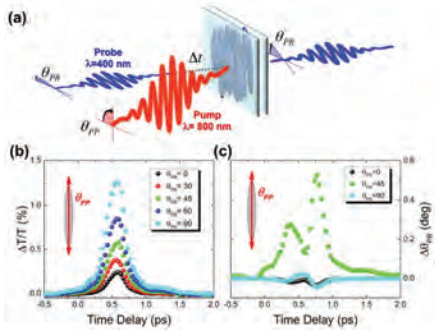


*Figure 16: Scheme of the pump-probe experiment and time dependence of the optically induced birefringence.*

### Ultrafast control of light by light in a nematic liquid crystal

A significant advancement was achieved with respect to the ultrafast all-optical response of a nematic liquid crystal. Two important experiments were reported by our group in 2015, in two publications in *Optics Express*. In collaboration with Radboud University, Nijmegen, the Netherlands, we measured the ultrafast optical response of a nematic liquid crystal, which is induced by an intense femtosecond optical impulse. It was observed in a pump-probe experiment (Figure 16), that a 100 fs optical pulse induces changes of the refractive index of the nematic liquid crystal, which are as fast as 500 fs. This is due to the optical Kerr effect and refractive-index changes of the order of $10^{-4}$ were observed at a fluence of 4 mJ/cm$^2$. The effect is strongly polarisation dependent and opens up new routes to all-optical liquid-crystal photonics. Published by Cattaneo et al., *Optics Express* 23, 14010 (2015).

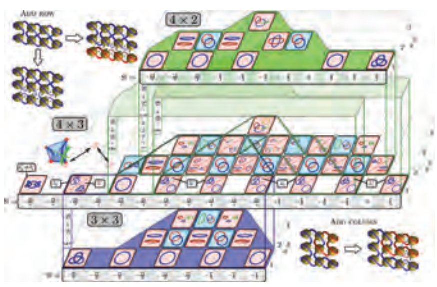


*Figure 17: The diagram classifies all nematic disclination configurations (from simple loops to links and knots) on a 4 × 3 colloidal grid, with marked structures that are just extensions of structures on sub-grids of dimensions 3 × 3 (blue outline) and 4 × 2 (green outline).*

### Nanosecond control of light by stimulated emission depletion in a liquid crystal

Stimulated emission depletion is used in STED microscopes to achieve the super-resolution of an optical microscope by manipulating the fluorescence emissions from dye molecules dissolved in a material. We have used the STED technique to control the emission of light in the smectic-A and nematic liquid crystal and observed strong attenuation of the optical signals on the nanosecond timescale. The STED effect is strongly polarisation dependent in liquid crystals because of the orientational order of fluorescent dies. This allows for gigahertz control of light, including light-gating and optical pulse-shaping with sub-nanosecond resolution. Published by Vitek and Muševič in *Optics Express* 23, 16921 (2015).

### Knot-theory realizations in nematic colloids

Knot theory is a branch of topology that deals with the study and classification of closed loops in 3D Euclidean space. The creation and control of knots in physical systems is the pinnacle of technical expertise, pushing forward state-of-the-art experimental approaches as well as a theoretical understanding of the topology in a selected medium. We showed how several abstract concepts manifest elegantly as observable and measurable features in nematic colloids with knotted disclination lines. The construction of medial graphs, surfaces, and Jones polynomials (Figure 17) was showcased directly on experimental images, and adapted for the specific system of colloidal crystals in a twisted nematic cell. Discussing the correspondence between topological concepts and experimental observation is essential for building the bridge between mathematical and physical communities. (S. Čopar et al., "Knot theory realizations in nematic colloids", *Proc. Natl. Acad. Sci.* 112, 1675 (2015)).

### Templated blue phases

Microscopic properties of templated liquid-crystal blue phases were demonstrated. Specifically, the role of surface anchoring on the microscopic ordering was explored, showing novel liquid-crystalline structures. The predicted structures exhibit the Kerr constant, which is several times larger than currently known in these materials, making templated blue phases interesting for optic and photonic applications. The work was performed as part of the Japanese JSPS Short-term invitation fellowship (M. Ravnik, 1.5 months), which was also the basis for a series of 9 invited seminars across Japan (Tokyo, Kyoto, Osaka, Kyushu, AIST). The paper (M. Ravnik and Jun-ichi Fakuda, "Templated blue phases", *Soft Matter* **11**, 8417 (2015)) was also announced by the inside cover of the Soft Matter journal (Figure 18).

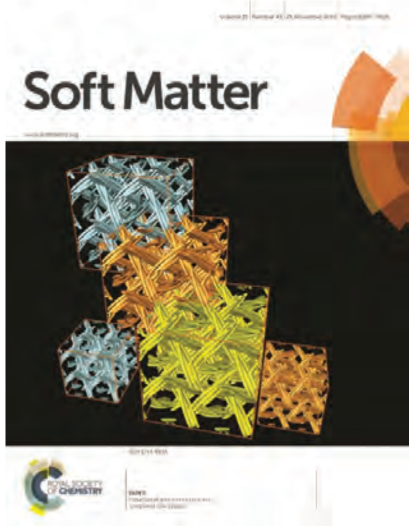


*Figure 18: Templated blue phases as a new photonic material, which is based on the micro-organisation of a nematic liquid crystal. The figure is the inside cover of one of the November issues of Soft Matter.*

### Topological defects within nematic shells

We have studied theoretically and numerically the impact of curvature on the position and the number of topological defects (TDs) in orientational ordering in effectively two-dimensional (2D) films. We used a 2D Landau-type mesoscopic approach, which we developed in 2013, in terms of nematic tensor order parameter. For illustrative purposes we considered mostly cylindrically symmetric dumb-bell and toroidal geometries. We demonstrated that curvature can impose geometric frustration, which enforces topological defects (Figure 19). Furthermore, interactions between the TDs in 2D display remarkable similarity with electrostatic interactions among the electric charges. Using the electrostatic analogy we derived a critical curvature induced condition at which pairs (defect, anti-defect) are created. The results are interesting both from the fundamental perspective as well as for potential applications in nano-photonics. The results were presented in several publications and in a plenary conference lecture. The key paper was D. Jesenek et al., *Soft Matter Soft* **11**, 2434–2444 (2015).

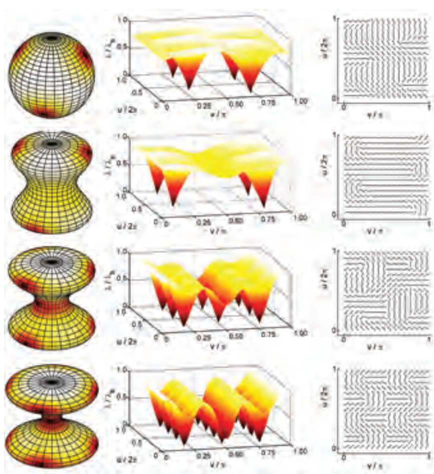

*Figure 19: Curvature-induced unbinding of topological defects in nematic shells. Geometry of the shells (the 1st row) and the corresponding order parameter (the 2nd row) and mesoscopic molecular field (the 3rd row) spatial variations.*

### New method of realignment in liquid-crystal displays

A new method for the realignment of nematic liquid crystals in surface-stabilized displays was presented. The realignment is carried out by controlled movement of an IR laser beam, which reorients LC molecules and consequently the aligning polymer layer due to the surface-memory effect. (G. Mirri et al., *Soft Matter*, 11, (2015), 3347). This method can be separately applied to both substrates of a LC display in different directions and small homogenous and twist-nematic domains can be created in planar cells (Figure 20).

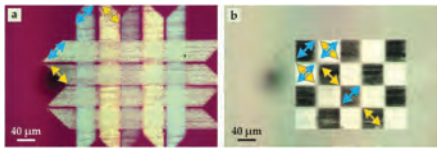


*Figure 20: LC realignment in a planar cell. (a) For one substrate alternating rows with molecular orientations of 45° and –45° with respect to the original horizontal LC alignment (blue and yellow arrows) were imprinted by laser realignment. For the other substrate, alternating columns of 45° and –45° were imprinted. (b) When the cell is backlit and viewed between crossed optical polarizers, the squares with a parallel orientation appear dark and the squares with a perpendicular orientation appear bright.*

### Stability of nanometre-sized colloidal liquid-crystal dispersions

We studied the motion of individual 20-nm nanoparticles in a nematic liquid crystal using dark-field microscopy and analysed particle pair interactions (Figure 21). We have shown that the stability of the dispersion of nanoparticles in a LC is a result of the balance of an attractive LC-mediated elastic force with a very weak interaction potential (below 10 $k_BT$) and a repulsive electrostatic force, which prevents the formation of permanent colloidal assemblies of a nanometre size (A. Ryzhkova et al., *Phys. Rev. E*, 91, (2015), 042505).

### Molecular motors

In 2015 we investigated the hydrodynamic synchronization of autonomous oscillators in collaboration with researchers from the University of Ljubljana. As oscillators we used ellipsoidal particles, which can spontaneously oscillate in a focused laser beam. We have shown that two particles in general synchronize in-phase and that the level of synchronization is stronger when the particles are arranged parallel to the direction of oscillations rather than perpendicular. In a narrow parameter range, anti-phase synchronization is also possible. A longer chain of oscillators shows correlations, but no complete synchronization of all the particles (Figure 22). We explained the results by describing the oscillating particles with a simple phenomenological model and calculating the hydrodynamic coupling numerically using a boundary-element method. Our study shows that

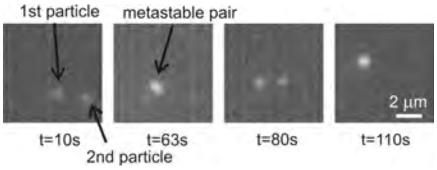


*Figure 21: Formation of a metastable pair of 20-nm silica particles in a nematic liquid crystal observed by dark-field microscopy.*

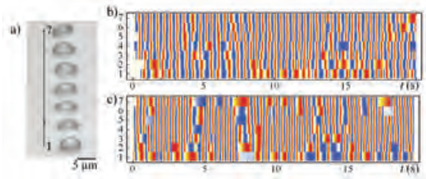

*Figure 22: a) A chain of 7 autonomous oscillators in a row. b) Measured phase profile of oscillations. c) Result of the theoretical model.*

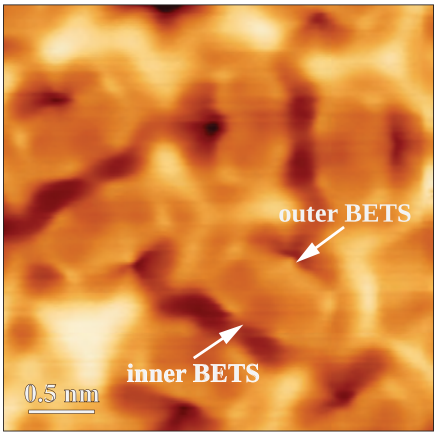


*Figure 23: High-resolution STM image showing details with the organic BETS molecules packed into a Kagome lattice on the Ag(111) surface (10.5 × 10.5 nm², T=1.1K, functionalized tip).*

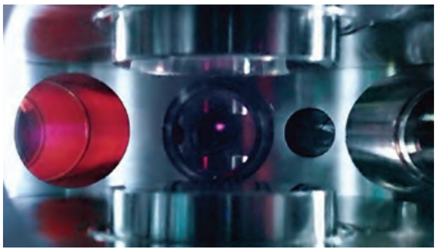

*Figure 24: View through one of the viewports into the UHV chamber, where due to fluorescence light about 50 million cold Cs atoms can be seen as a small pink ball.*

self-oscillating particles can act as a model system for the synchronization between biological cilia. Although several model systems for hydrodynamic synchronization were published previously, ours was the first to use truly autonomous microscopic oscillators. The results were published in *Physical Review E (Rapid Communication),* where the paper was also highlighted as the Editor's suggestion.

### $MoO_3$ nanowires and nanotubes

We synthesized $MoO_3$ nanowires and nanotubes from $Mo_6S_2I_8$ nanowires via oxidation in air. The orthorhombic α-$MoO_3$ phase has been determined from XRD data and Raman spectroscopy. The porosity of the nanowires and faceting tendency of the nanotubes were explained by the density and molar mass change during oxidation and the layered structure of α-$MoO_3$, respectively. An additional broad Raman band at 1004 $cm^{-1}$ was clearly observed and attributed to missing oxygen. An EPR investigation showed that the extent of oxygen deficiency is large enough for the appearance of crystal shear planes typical for Magneli phases (A. Varlec et al., *Materials Chemistry and Physics* 170 (2016) 154-161), which strongly influence the physical properties of these nanomaterials. A high specific surface (14.3 m2/g) and water solubility enable the application of these nanomaterials in anti-bacterial coatings.

### $MoS_2$ nanotubes in field-effect transistors

$MoS_2$ nanotubes and nanoribbons synthesized by a chemical transport reaction two decades ago at the JSI found their application in a new generation of field-effect transistors (FETs) due to the very low density of structural defects. Devices demonstrated n-type characteristics with ON/OFF current ratios of more than $10^3$, greatly exceeding the best prior report of 60 in the $MoS_2$ nanotubes prepared in other ways. Current densities were 1.02 µA/µm and 0.79 µA/µm at $V_{DS}$=0.3V and $V_{BG}$=1V, respectively. Photocurrent measurements conducted on a $MoS_2$ nanotube FET using Ti/Au contacts revealed a short-circuit photocurrent of tens of nano-amps under an excitation optical power of 78 µW and a 488-nm wavelength, which corresponds to a responsivity of 460 µA/W (S. Fathipour, et al., Applied Physics Letters 106 (2015) 022114).

### Nanoscale organic superconductors

The ability to fabricate crystalline monolayers of confined superconducting condensates on surfaces is a key issue to realize new functionalities and understand the nature of competing orders in these materials at the nanoscale. The epitaxial growth of insulating or superconducting monolayer islands of an organic charge-transfer salt $(BETS)_2GaCl_4$ on Ag(111) has been achieved at various growth temperatures. Below 125 K the BETS molecules form chain-like or regular two-dimensional networks. Above 125 K, the BETS dimers start to alternate regularly along the three equivalent orientations of the <110> packing directions, forming an insulating Kagome lattice with a triangular nanoporous network (Figure 23). When the deposition is carried out at room temperature and at low deposition currents (monolayer) islands showing a superconductive gap in the density of states are grown (A. Hassanien et. al, *Phys. Stat. Sol. (B)*, 252 (2015), 2574).

### Ultra-cold atoms

For the first time Cs atoms were trapped and cooled in the Laboratory for Cold Atoms. Using 852-nm laser light hot Cs atoms are first slowed down and then trapped in a magneto-optical trap using a quadrupole magnetic field (Figure 24). In a process called Raman sideband cooling their temperature is decreased to below 500 nK. In the next steps these atoms will be loaded into a strong dipole trap where they will be compressed and additionally evaporatively cooled to temperatures below 50 nK. At such low temperatures a transition to the Bose-Einstein condensate will be achieved.

## *III. Research programme Experimental biophysics of complex systems*

In the program "**Experimental biophysics of complex systems**", processes and structures of various complex biological systems are investigated, ranging from model systems to the structures in living cells, tissues and small animals. Investigations also comprise studies of the impact of numerous bioactive substances such as toxins and drugs as well as a variety of materials from materials to medical materials on such biological systems. The research is lately focused on a better understanding of the structure of membrane compartments, domains, proteins, glyco- saccharides clusters, molecular structures of polymer gels, etc. and their interaction, accompanying the interaction of cell structures with new materials that enter into their natural environment. New spectroscopic and micro-spectroscopic techniques contribute to a better understanding of the organization of these supramolecular systems, complex cellular and tissue responses and open up new possibilities for the design of medical materials, especially for tissue regeneration, which is one of the main health issues among the aging population of the developed world. In addition, the research field is also directed to optimization methods for the treatment of tumours, magnetic resonance imaging and the mathematical modelling of thrombolysis, and the use of high-resolution magnetic resonance imaging to study materials. This method allows us to study different problems in forestry, the wood industry, and food safety. We expect a lot from the development of new methods for measuring diffusion in porous materials with which we will be able to tell a lot about the microscopic structure of porous materials.

**The cell-adhesion dynamics was quantitatively studied via optical-tweezers force-induced displacements of loosely bound cells which reveal that the adhesion strength correlates with the scaffold's polymer molecular mobility and has a direct impact on further cell growth, measured on a scale of days. We have developed new methods to monitor food processing and food quality control based on multiparametric MR imaging. In addition, a new method that allows an accurate determination of the deformation tensor of soft samples has also been developed.**

The **cell-material interaction studies**, especially from the viewpoint of bioactivity and biocompatibility, are undoubtedly one of the hottest biophysics research topics. Based on new micro-spectroscopies we efficiently address the problem of nanoparticles and nanofibers uptake into the cell or the model membrane. Uptake into and through the membrane was proven by the FMS-FRET-experiments acquired on model membranes. We also explored the effect of the properties of nanoparticles, such as their size and their surface properties, on the interaction of the nanoparticles with biological systems. As a result, some methods to control the size and the surface properties of the nanoparticles have also been undertaken.

Based on our previous research focused on measuring the impact of the physical properties of 3D porous biopolymer scaffolds as tissue-engineering materials on cell growth, published last year in a journal with an impact factor of 5.9 (*ACS Appl. Mater. Interfaces*, 2014; 6 (18), pp 15980 to 15990), the focus in 2015 was on the interaction between scaffold surfaces and cells in real time. With the **optical-tweezers system** for optical micro-manipulation built within the **confocal fluorescence microscope system**, the adhesion dynamics of the cells on the surfaces of different biocompatible tissue engineering scaffolds with different surface molecular physical properties was investigated (Figure 25). The time window and the dynamics of the adhesion sites' formation on the cell-material interface was quantitatively determined by submicron-resolution, optical-tweezers, force-induced, displacement analysis of a loosely bound cell. It was found that the adhesion strength on the surfaces of different scaffolds correlates with the scaffolds' polymer molecular mobility and has a direct impact on further cell growth, measured on a scale of days. The study was published in a journal with an impact factor of 6.7 (*ACS Appl. Mater. Interfaces*, 2015, 7 (12), pp 6782-6791). The developed experimental system for studying the direct contact of cells with tissue-engineering materials in real time could, with some additional future optimizations, contribute to a better understanding of the biocompatibility of materials, which is one of the main challenges in the field of tissue engineering and regenerative medicine.

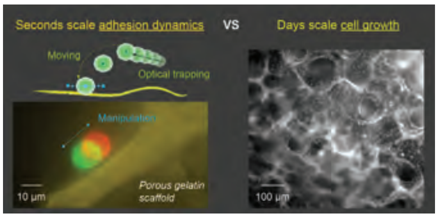


*Figure 25: Real-time cell-adhesion dynamics analysis on the surfaces of tissue-engineering scaffolds using optical micromanipulation and fluorescence detection (left) serves as an efficient method for studying scaffolds' biocompatibility (right).*

**Fluorescence microspectroscopy (FMS)** reveals the physical properties of the molecular environment of fluorescent probes. In this respect specific probes can be designed and synthesized to enhance the sensitivity to a particular property, for example, a local pH value. This approach was applied to **study the internalization in dendritic cells** (DCs) the most potent antigen-presenting cells. DC-SIGN, an antigen-uptake receptor in DCs, has a clear **role in the immune response** but can, conversely, also facilitate infection by providing the entry of pathogens to DCs. The key action in both processes is internalization to acidic endosomes and lysosomes. Molecular probes that bind to DC-SIGN could thus provide a useful tool to study internalization and, at the same time, constitute potential antagonists against pathogens. Our strategy, therefore, was to **develop a smart fluorescent probe** with an affinity for DC-SIGN (Figure 26). Two particular properties of the probe were exploited: **activation in a low-pH environment and an aggregation-induced spectral shift**. The results indicate that our probe is successfully internalized in DCs. Moreover, the concentration of the probe increases inside the cells with the time of incubation leading to aggregation. Since the expected spectral shifts due to aggregation are small – in the range of a few nanometres – conventional fluorescence microscopy with broad band-pass emission filters is not an appropriate experimental approach. In contrast, a spectrally highly sensitive FMS method permits the detection of highly precise shapes of emission spectra. In this way, the features of the smart probe could be exploited to monitor its targeting to and aggregation in low-pH cell structures.

In an article published in *PLOSONE* we explored **the role of serum proteins in the phototoxicity of $TiO_2$ nanoparticles**. We measured the viability of the exposed cells depending on the nanoparticle and serum protein concentrations. Our data indicate that the phototoxicity only becomes substantial when the protein concentration is too low to completely coat the nanotubes' surface. These results imply that $TiO_2$ nanoparticles should be applied with ligands such as proteins when phototoxic effects are not desired – for example, in the cosmetics industry. On the other hand, the nanoparticles should be used in a serum-free medium or any other ligand-free medium, when phototoxic effects are desired – like for efficient photodynamic cancer therapy (PLoS One 2015 10 (6):e012957).

Our unpublished results indicate that the formation of a lipid corona is possible, where the nanoparticle is wrapped with a lipid membrane. We hypothesize that such lipid-wrapped nanoparticles may resemble lipid vesicles derived from platelets, usually known as "microparticles". An important characteristic of microparticles is that the key reaction of **blood coagulation** takes place on them, the **activation of factor Xa**. Last year we published our work showing that the regulation of the activity of Factor Xa depends critically on the concentration of calcium in the plasma and that this process is likely to be physiologically important in the initial stage of blood clotting. This year we continued our collaboration with prof. Lentz's laboratory from the University of North Carolina, resulting in another publication in the *Biochemical Journal*, which is one of the world's leading bioscience journals (Impact Factor (2013): almost 5 (ranked 61st out of 291 journals in the Biochemistry and Molecular Biology category, established 1906). We showed that at $Ca^{2+}$ concentrations found in the maturing platelet plug (2–5 mM), fVa can compete fXa off of inactive fXa dimers to significantly amplify thrombin production, both because it releases dimer inhibition and because of its well-known cofactor activity. This suggests a novel, hitherto unanticipated, mechanism by which PS-exposing platelet membranes can regulate the amplification and propagation of blood coagulation (*Biochem. J.* 2015 (467):37).

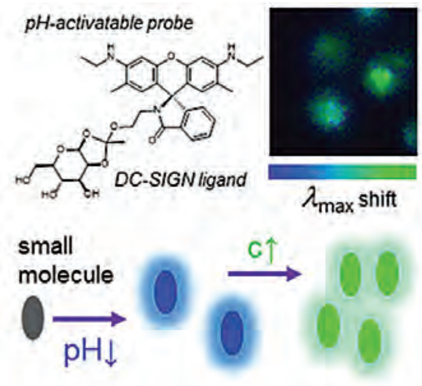

*Figure 26: A smart fluorescent probe was synthesized to monitor internalization by the DC-SIGN receptor in dendritic cells (DCs). Its activation and accumulation in low-pH cell structures were spectrally detected. Such molecules could compete with pathogens for binding both outside and inside DCs.*

In cooperation with researchers from the Agricultural Institute of Slovenia we published a paper entitled "Use of multiparametric magnetic resonance microscopy for discrimination among different processing protocols and anatomical positions of Slovenian dry-cured Hams." in the journal *Food Chemistry*. The paper deals with the possibility of using new methods of **characterization for the dry-curing process of meat products**, which are based on the use of **multiparametric magnetic resonance (MR) imaging**. More specifically, relaxation time T1 and T2 mapping, and the apparent diffusion constant (ADC) mapping were used to find the differences between two different ham muscles (biceps femoris and semi-membranosus) at two different stages of salting (low and high). In this paper, we showed that the maps can be converted into one-dimensional distributions of the parameters T1, T2 and ADC and in two-dimensional correlations between the parameters ADC-T2, ADC-T1, T1-T2, which show characteristic peaks in the distribution. The location and distribution of these peaks are very sensitive to both types of tissue, as well as the influence of the salting. The characterization was better with a two-dimensional correlation than with one-dimensional distributions. We concluded that these methods having greater accessibility to NMR/MRI systems can serve as an effective tool for monitoring the processing of dry-cured meat products, as well as to control their quality. In the field of MR imaging in food science we have also published an article "MR microscopy for noninvasive detection of water distribution during soaking and cooking and the common bean". The paper deals with the role of water in the soaking and cooking of legumes. The water in the seeds of legumes is bound, and therefore has a short T2 relaxation time, while the surrounding water has a long T2 relaxation time. These two different types of water can be detected by different NMR/MRI methods. In the study we used the SPI method to detect the bound water and the RARE method to detect free water. Both methods were used for dynamic imaging, so that we were able to monitor the changing role of water in the process of soaking and cooking the seeds.

We developed a method for **high-resolution MR imaging of mechanical deformations**. The method is based on the use of the pulsed magnetic field gradients that can encode the initial (before deformation) and the final (after deformation) position of each volume element of the studied sample. It turns out that the difference in the positions is proportional to the phase shift of the signal (Figure 27). With this method we measured the strain tensor of the gelatin sample. In addition to the pulse sequence we also developed a special deformational device that was used to dynamically trigger a sample deformation of the desired magnitude. The device had to perform sample deformations synchronously with the imaging sequence. The method was presented in an article "Magnetic Resonance Imaging of mechanical deformations" published in the journal *Magnetic resonance imaging*.

The cooperation with the group of prof. Eung Je Woo from Kyung Hee University in the Republic of Korea continued in 2015. With this group, we published an article entitled "Frequency-dependent conductivity contrast for tissue characterization using a dual-frequency range conductivity mapping magnetic resonance method", which was published in the renowned journal IEEE Transactions on Medical Imaging. In this paper we introduced a new method of conductivity imaging, which can simultaneously acquire two sets of data that are then used for the calculation of conductivity images at two different frequency ranges. One at low (DC) frequencies and the other at high radio (RF) frequencies.

In 2015 we also started using our new 400-MHz system for MR microscopy of more challenging samples. On the system we carried out extensive measurements for the determination of the effect of impregnation on water penetration in wood. The measurements were carried out with different types of wood (pine, spruce, chestnut, etc.)

as well as with various wood treatments (oiling, waxing, etc.). This study is a result of our cooperation with the group of Prof. Miha Humar from the Department of Biotechnical Faculty in Ljubljana. The second half of the year was marked by the visit of two visitors from Norway, namely, Prof. John G. Seland and Dr. Tina Pavlin. Prof. Seland was in our laboratory on sabbatical. The theme of his scientific work was measurements of restricted diffusion in porous materials for which he used the method of modulated magnetic field gradients (MGSE), which was developed in our laboratory.

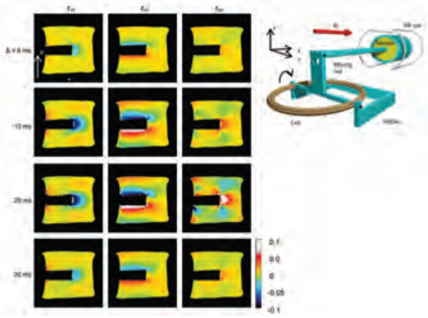

*Figure 27: Maps of normal ($\varepsilon_{zz}$, $\varepsilon_{yy}$) and shear ($\varepsilon_{yz}$) strain components of the deformed sample for different deformation times Δ = 6, 10, 20, 30 ms. A colour-coded scale represents strains in the range -0.1–0.1. The sample deformations were induced by a deformational device shown in the upper-right corner.*

Our research has been supported by a number of international projects financed by the European Union within the 6th and 7th Frameworks. It was also supported within the bilateral Slovenia–USA, Slovenia–Germany, Slovenia–Greece and other scientific cooperations. In 2015, the Department had cooperations with 108 partners from Slovenia and abroad. Among them:

- The high-magnetic-field centres in Grenoble, France, and Nijmegen, The Netherlands
- The high-magnetic-field centre at the University Florida, Tallahassee, Florida, USA
- The ETH, Zürich, Switzerland
- The Ioffe Institute in St. Petersburg, Russia
- The University of Duisburg, the University of Mainz and the University of Saarbrucken in Germany
- The University of California, the University of Utah and the Liquid Crystal Institute, Kent, Ohio, USA,
- National Institute for Research in Inorganic Materials, Tsukuba, Japan
- NCSR Demokritos, Greece
- Institut für Biophysik und Nanosystemforschung OAW, Graz, Austria
- Bioénergétique et Ingénierie des Protéines, CNRS Marseille, France
- Architecture et Fonction des Macromolécules Biologiques, CNRS Marseille, France
- The Max Delbruck Center for Molecular Medicine in Berlin
- The Dartmouth Medical School, Hanover, NH, USA
- The Mayo Clinic, Rochester, USA
- Kyung Hee University, Suwon, Korea
- Technische Universität Ilmenau, Ilmenau, Germany
- Elettra Sincrotrone Trieste, Trieste, Italy
- University if North Carolina at Chapel Hill
- Max-Delbrück-Centrum für Molekulare Medizin (MDC)

made the above studies possible.

## Some outstanding publications in 2015


1. M. Pregelj, A. Zorko, O. Zaharko, H. Nojiri, H. Berger, L. Chapon, D. Arčon. Spin-stripe phase in a frustrated zigzag spin-1/2 chain. *Nature Communications* 6, 7255(2015).
2. M. Klanjšek, D. Arčon, A. Sans, P. Adler, M. Jansen, C. Felser. Phonon-modulated magnetic interactions and spin Tomonaga-Luttinger liquid in the p-orbital antiferromagnet $CsO_2$. *Physical Review Letters* 115, 057205(2015).
3. R. H. Zadik, A. Potočnik, P. Jeglič, D. Arčon, et al. Optimized unconventional superconductivity in a molecular Jahn-Teller metal. *Science Advances* 1, e1500059(2015).
4. M. Pregelj, A. Zorko, M. Gomilšek, et al. Controllable broadband absorption in the mixed phase of metamagnets. *Advanced Functional Materials* 25, 3634 (2015).
5. M. Nikkhou, M. Škarabot, S. Čopar, M. Ravnik, S. Žumer, I. Muševič. Light-controlled topological charge in a nematic liquid crystal. *Nature Physics* 11, 183 (2015).
6. S. Čopar, U. Tkalec, I. Muševič, S. Žumer. Knot theory realizations in nematic colloids. *Proc. Natl. Acad. Sci.* 112, 1675 (2015)).
7. R. Podlipec, J. Štrancar. Cell-scaffold adhesion dynamics measured in first seconds predicts cell growth on days scale - optical tweezers study. *ACS Applied Materials & Interfaces* 7, 6782(2015).
8. T. Koklič, R. Chattopadhyay, R. Majumder, B. R. Lenz. Factor Xa dimerization competes with prothrombinase complex formation on platelet-like membrane surfaces. *Biochemical Journal* 467, 37(2015).
9. Z. Arsov, U. Švajger, J. Mravljak, S. Pajk, A. Kotar, I. Urbančič, J. Štrancar, M. Anderluh. Internalization and accumulation in dendritic cells of a small pH-activatable glycomimetic fluorescent probe as revealed by spectral detection. *ChemBioChem* 16, 2660(2015).

## Some outstanding publications in 2014


1. A. Zorko, O. Adamopoulos, M. Komelj, D. Arčon, A. Lappas. Frustration-induced nanometre-scale inhomogeneity in a triangular antiferromagnet. Nature Comms 5, 3222 (2014).
2. P. Koželj, S. Vrtnik, A. Jelen, S. Jazbec, Z. Jagličić, S. Maiti, M. Feuerbacher, W. Steurer, J. Dolinšek, Phys. Rev. Lett. **113**, 107001 (2014).
3. R. Pirc, B. Rožič, J. Koruza, B. Malič, Z. Kutnjak, Negative electrocaloric effect in antiferroelectric $PbZrO_3$. Europhysics Letters 107, 17002-1-5(2014).
4. A. Martinez, M. Ravnik, B. Lucero, R. Visvanathan, S. Žumer, and I.I. Smalyukh Mutually tangled colloidal knots and induced defect loops in nematic fields, Nature Mater. 13, 258-263 (2014).
5. D. Seč, S. Čopar and S. Žumer, Topological zoo of free-standing knots in confined chiral nematic fluids, Nature Comms. 5, 3057 (2014).
6. J. Dontabhaktuni, M. Ravnik and S. Žumer, Quasicrystalline tilings with nematic colloidal platelets, Proceedings of the National Academy of Sciences of the United States of America 111, 2464 (2014).
7. S. Čopar, Topology and geometry of nematic braids, Phys. Rep. 538, 1-37 (2014).
8. A. Vilfan, Myosin directionality results from coupling between ATP hydrolysis, lever motion, and actin binding. Proceedings of the National Academy of Sciences of the United States of America 111, E2076 (2014).
9. Urbančič, I., Ljubetič, A. & Štrancar, J. Resolving Internal Motional Correlations to Complete the Conformational Entropy Meter. J. Phys. Chem. Lett. 5, 3593–3600 (2014).
10. Podlipec, R. et al. Molecular Mobility of Scaffolds' Biopolymers Influences Cell Growth. ACS Appl. Mater. Interfaces 6, 15980–15990 (2014).
11. Mikhaylov, G. et al. Selective targeting of tumor and stromal cells by a nanocarrier system displaying lipidated cathepsin B inhibitor. Angew. Chem. Int. Ed Engl. 53, 10077–10081 (2014).


## Some outstanding publications in 2013


1. S. Vallejos, P. Umek, T. Stoycheva, F. Annanouch, E. Llobert, X. Correig, P. de Marco, C. Bittencourt, Ch. Blackman. Single-step deposition of Au- and Pt-nanoparticle-functionalized tungsten oxide nanoneedles synthesized via aerosol-assisted CVD, and used for fabrication of selective gas microsensor arrays. Advanced Functional Materials 23, 1313-1322(2013).
2. A. Gradišek, D. Bomholdtravnsbaek, S. Vrtnik, A. Kocjan, J. Lužnik, T. Apih, T. Jensen, A. V. Skripov, J. Dolinšek. NMR study of molecular dynamics in complex metal borohydride $LiZn_2$ $BH_{45}$. Journal Phys. Chem. C 117, 21139-21147(2013).
3. M. Pregelj, A. Zorko, O. Zaharko, P. Jeglič, Z. Kutnjak, Z. Jagličič, S. Jazbec, H. Luetkens, A. D. Hillier, H. Berger, D. Arčon. Multiferroicity in the geometrically frustrated $FeTe_2O_5Cl$. Phys. Rev. B 88, 224421-1- 10(2013).
4. A. Nych, U. Ognysta, M. Škarabot, M. Ravnik, S. Žumer, I. Muševič. Assembly and control of 3D nematic dipolar colloidal crystals. Nature Communications 4, 1489-1-8 (2013) doi: 10.1038/ncomms2486. 2013,
5. V. S. R. Jampani, M. Škarabot, S. Čopar, S. Žumer, I. Muševič. Chirality screening and metastable states in chiral nematic colloids. Phys. Rev. Lett.110, 177801-1-5(2013).
6. S. Novak, D. Drobne, L. Vaccari, M. P. Kiskinova, P. Ferraris, G. Birarda, M. Remškar, M. Hočevar. Effect of ingested tungsten oxide ($WO_X$) nanofibers on digestive gland tissue of Porcellio scaber (Isopoda, Crustacea) : fourier transform infrared (FTIR) imaging. Env. Sci. & Tech. 47, 11284-11292(2013).
7. F. Bajd, I. Serša. Mathematical modeling of blood clot fragmentation during flow-mediated thrombolysis. Bioph. Journal 104, 1181-1190(2013).
8. I. Urbančič, A. Ljubetič, Z. Arsov, J. Štrancar. Coexistence of probe conformations in lipid phases: a polarized fluorescence microspectroscopy study. Bioph. Journal 105 919-927(2013).


## Awards and appointments

1. Samo Kralj: Reward for outstanding educational achievements and constantly highest marks in students' assessments from Faculty of Natural Sciences and Mathematics, University of Maribor, 2015
2. Samo Kralj: Golden Reward from Society for Technical Culture of Slovenia for outstanding achievements in the field of education, 2015
3. Samo Kralj: Distinguished referee reward of the European Physical Journal in 2015
4. Matjaž Humar: Name of the week (VAL 202)
5. Matjaž Humar: Personality of Primorska region for the month of July 2015

## Organization of conferences, congresses and meetings

1. Training School "Bottom-up Approaches of Hybrid materials: Preparation and Design", 26. 5. – 28. 5. 2015

## Patents granted

1. Andraž Rešetič, Jerneja Milavec, Blaž Zupančič, Boštjan Zalar, Polymer dispersed liquid crystal elastomers, SI24658 (A), Slovenian Intellectual Property Office, 30. 09. 2015.
2. Maja Remškar, Janez Jelenc, Andrej Kržan, Fluoro-polymer nanocomposites with tailored friction properties, SI24472 (A), Slovenian Intellectual Property Office, 31. 03. 2015.
3. Maja Remškar, Ivan Iskra, Marko Viršek, Mark Pleško, Damjan Golob, Method and capacitive sensor for counting aerosol nanoparticles, US9151724 (B2), US Patent Office, 6. 10. 2015.
4. Aleš Mrzel, Maja Remškar, Adolf Jesih, Marko Viršek, Process for the synthesis of nanotubes and fullerene-like nanostructures of transition metal dichalcogenides, quasi one-dimensional structures of transition metals and oxides of transition metals, EP2132142 (B1), European Patent Office, 5. 08. 2015.
5. Igor Muševič, Matjaž Humar, Spherical liquid-crystal laser, EP2638604 (B1), European Patent Office, 18. 03. 2015.

# INTERNATIONAL PROJECTS

1. MERCK - AFM Investigations
   Asst. Prof. Miha Škarabot
   Merck Kgaa
2. Development of Curved LCD Shutter
   Prof. Igor Muševič
   Kimberly-Clark
3. Kimberly-Clark-2015 - Development of Prototype Curved LCD Shutter
   Prof. Igor Muševič
   Kimberly-Clark
4. 7FP - LEMSUPER; Light Element Molecular Superconductivity: An Interdisciplinary Approach
   Prof. Denis Arčon
   European Commission
5. 7FP - ESNSTM; Electron Spin Noise Scanning Tunneling Microscopy
   Prof. Janez Dolinšek
   European Commission
6. 7FP - NanoMag; Magnetic Nanoparticles and Thin Films for Spintronic Applications and High Performance Permanent Magnets
   Prof. Janez Dolinšek
   European Commission
7. 7FP - SIMDALEE2; Sources, Interaction with Matter Detection and Analysis of Low Energy Electrons 2
   Prof. Maja Remškar
   European Commission
8. 7FP - NEMCODE; Controlled Assembly and Stabilisation of Functionalised Colloids in Nematic Liquid Crystals
   Prof. Igor Muševič
   European Commission
9. 7FP - LIVINGLASER; A Laser made Entirely of Living Cells and Materials derived from Living Organisms
   Prof. Igor Muševič
   European Commission
10. 7 FP; ERA CHAIR ISO-FOOD - Era Chairs for Isotope Techniques in Food Quality, Safety and Traceability
    Prof. Maja Remškar
    European Commission
11. COST MP1202; HINT School
    Dr. Polona Umek
    Cost Office
12. COST MP1103; Nanostructured materials for solid-state hydrogen storage
    Dr. Anton Gradišek
13. Low Dimensional Structures of Metal Sulfides and Selenides for Use in Transistor Electronics
    Prof. Maja Remškar
    Slovenian Research Agency
14. Local Studies of Frustrated Quantum Antiferromagnets
    Dr. Andrej Zorko
    Slovenian Research Agency
15. Key Role of Magnetic Anisotropy in Low-dimensional Spin Systems
    Dr. Andrej Zorko
    Slovenian Research Agency
16. Hybrid Solar Cell Based on Conducting Polymers and 1D Nanostructured TiO2
    Dr. Polona Umek
    Slovenian Research Agency
17. Spin-liquid Ground State of Quantum Kagome Antiferromagnets from a Local-probe Perspective
    Dr. Andrej Zorko
    Slovenian Research Agency
18. Controlled Nanoparticle Assemblies in Complex Soft Matrices
    Prof. Samo Kralj
    Slovenian Research Agency
19. Crystal and Electronic Structure of Quasi One-dimensional Transition-metal Chalcogenides
    Dr. Erik Zupanič
    Slovenian Research Agency
20. Radiative forcing of desert mineral dust and PM10 concentrations over Southern Europe
    Prof. Maja Remškar
    Slovenian Research Agency

# RESEARCH PROGRAMS

1. Experimental Biophysics of Complex Systems
   Prof. Janez Štrancar
2. Physics of Soft Matter, Surfaces and Nanostructures
   Prof. Slobodan Žumer
3. Magnetic resonance and dielectric spectroscopy of "smart" new materials
   Prof. Janez Dolinšek

# R & D GRANTS AND CONTRACTS

1. Topology and Photonics of Liquid Crystal Colloids and Dispersions
   Prof. Igor Muševič
2. Intra-pocket-targeted nanomedicines for treatment of periodontal disease
   Prof. Maja Remškar
3. The textural analysis of spatiotemporal changes for breast lesions diagnosis on ultrafastbreast MRIs
   Prof. Igor Serša
4. Optimization strategies in biological and artificial microfluidic systems
   Asst. Prof. Andrej Vilfan
5. Thermophoretic guidance, accumulation and sorting of biomolecules in microfluidic devices
   Asst. Prof. Andrej Vilfan
6. New advanced electrocaloric materials for novel environmentally-friendly dielectric refrigeration technology
   Prof. Zdravko Kutnjak
7. Role of Calcium and lipid membranes in survival of critically ill patients
   Dr. Tilen Koklič
8. Selective and hipersensitive microcapacitive sensor system for targetted molecular detection in the atmosphere
   Prof. Igor Muševič

9. Water exclusion efficacy, measure for prediction of wood performance against wood decay fungi
Prof. Igor Serša
10. Micro-electromechanical and electrocaloric layer elements
Prof. Zdravko Kutnjak
11. Light-controlled layer-by-layer formation of scaffolds for faster tissue regeneration
Dr. Iztok Urbančič
Ministry of Education, Science and Sport
12. New polymer and ceramic materials for potential use in capacitors
Dr. Andreja Eršte
Ministry of Education, Science and Sport
13. SCOPES; Spin-liquid and Spin-ice States in Frustrated Rare-earth and Transition Metal Spinels
Dr. Matej Pregelj
SNF- Swiss National Science Foundation
14. Nanomaterials and Scaffolds preparation and characterization
Prof. Janez Štrancar
Ministry of Education, Science and Sport
15. Irradiation and Analysis of Nano Si Samples
Prof. Vid Bobnar
Institute Of Radiation Problems Of Aznas
16. Irradiation and Analysis of Nano SiC Samples
Prof. Vid Bobnar
National Nuclear Research Center

# VISITORS FROM ABROAD

1. Prof. dr. Myung-Hwa Jung, Sogang University, Department of Physics, Seoul, South Korea, 1. 1. 2015-31. 8. 2015
2. Dr. Anna Ryzhkova, ASML, Eindhoven, Netherlands, 26.1.2015 - 22.2.2015, 18. 10. 2015 – 15. 11. 2015
3. Mag. Marketa Havrdova, Palacky University Olomouc, Department of Science, Czech Republic, 30.1.2015 – 20.2.2015, 29.3.2015 – 30.4.2015, 2.10. 2015 – 12.11.2015
4. Prof. dr. Sergey Lushnikov, IOFFE Physical-Technical Institute of the Russian Academy of Sciences, St. Petersburg, Russia, 2.2.2015 – 30.6.2015
5. Dr. Amal Kasry, Austrian Institute of Technology (AIT), Biosensor Technologies Department, Vienna, Austria, 5.2.2015 – 7.2.2015
6. Prof. dr. Igor Lukyanchuk, University of Picardie Jules Verne, Amiens, France, 15.2.2015 – 21.2.2015
7. Dr. Carla Bittencourt, Universite de Mons, Belgium, 10.3.2015 – 15.3.2015
8. Dr. Valentina Domenici, Dipartimento di Chimica e Chimica Industriale, University of Pisa, Pisa, Italy, 23.3.2015 – 28.3.2015, 14.12. – 18.12.2015
9. Vanessa Cresta, University of Pisa, Pisa, Italy, 1. 4. 2015 – 31. 8. 2015
10. Prof. Horst Beige, Martin Luther University, Halle, Germany, 21.4. – 26.4.2015
11. Dr. Ioannis Lelidis, University of Athens, Department of Physics, Athens, Greece, 22.4.2015 – 26.4.2015
12. Dr. George Nounesis, NCSR Demokritos, Athens, Greece, 22.4.2015 – 26.4.2015, 24.11.2015 – 27.11.2015
13. Mag. Katarina Jovanović, Institute for Oncology and Radiology of Serbia, Belgrade, Serbia, 4. 5. 2015 - 3. 7. 2015
14. Dr. Mirta Herak, Institute of Physics, Zagreb, Croatia, 8. 5. 2015, 8. 6. 2015 – 11. 6. 2015, 3. 11. 2015, 17.12. – 22.12.2015
15. Prof. dr. Alan C. Seabaugh, Notre Dame University, Department for Electrical Engineering, Indiana, USA, 10. 5. 2015 – 17. 5. 2015
16. Mag. Bouchra Asbani, Universite de Picardie Jules Verne, Laboratorie de Physique de la Mateiere Condensee, Amiens, France, 10. 5. 2015 – 31. 5. 2015
17. Dr. Marko Gosak, Fakulteta za narovoslovje in matematiko, Inštitut za fiziologijo Univerze v Mariboru, Maribor, 14. 5. 2015
18. Prof. Siegfied Dietrich, Max–Planck Institut für Intelligente Sisteme & Institut für Theoretische Physik IV, Universität Stuttgart, Stuttgart, Germany, 1. 6. 2015
19. Dr. Magdalena Wencka, Institute of Molecular Physics, Polish Academy of Sciences, Poznan, Poland, 1.6.2015 – 15.6.2015, 20. 9. 2015 – 20. 10. 2015
20. Dr. Nina Kravets, Nonlinear Optics and Optoelectronics Laboratory, Roma Tre University, Rome, Italy, 3. 6. 2015 – 7. 6. 2015
21. Etienne Brasselet, University of Bordeaux, France, 14.6.2015 – 17.6.2015
22. Dr. Ivana Capan, Ruđer Bošković Institute, Zagreb, Croatia, 10. 7. 2015 – 12. 7. 2015
23. Mateo Palleo, Stelar s.l.r., Mede, Italy, 20.7.2015 – 22.7.2015
24. Prof. John Georg Seland, University of Bergen, Bergen, Norway, 1. 8. 2015 – 31. 12. 2015
25. Dr. Tina Pavlin, University of Bergen, Bergen, Norway, 1. 8. 2015 – 31. 12. 2015
26. Dr. Yishay Feldman, Weizmann Institute of Science, Rehovot, Israel, 3. 8. 2015
27. Dr. Mutsuo Igarashi, Gunma National college of Technology, Maebashi, Japan, 12. 8. 2015 – 24. 8. 2015, 19. 10. 2015 – 27. 10. 2015
28. Prof. Aysegul Oksuz, Suleyman Demirel University, Faculty of Arts and Science, Isparta, Turkey, 21. 8. 2015 – 28. 8. 2015
29. Prof. Lutfi Oksuz, Suleyman Demirel University, Faculty of Arts and Science, Isparta, Turkey, 21. 8. 2015 – 28. 8. 2015
30. Prof. Qiming Zhang, The Pennsylvania State University, Pennsylvania, USA, 23. 9. 2015 – 25. 9. 2015
31. Prof. Francesca Ferlaino, University of Innsbruck, Research department, Innsbruck, Austria, 28. 9. 2015 – 29. 9. 2015
32. Adrien Chauvin, Institut des Materiaux Jean Rouxel, Nantes, France, 3. 10. 2015 – 11. 10. 2015
33. Dr. Vadim Pokrovskii, V.A. Kotelnikov Institute of Radioengineering and Electronics of Russian Academy of Sciences, Moskow, Russia, 26. 10. 2015 – 31. 10. 2015
34. Dr. Sergey Zybtsev, V.A. Kotelnikov Institute of Radioengineering and Electronics of Russian Academy of Sciences, Moskow, Russia, 26. 10. 2015 – 31. 10. 2015
35. Dr. Irina Gorlov, V.A. Kotelnikov Institute of Radioengineering and Electronics of Russian Academy of Sciences, Moskow, Russia, 26. 10. 2015 – 31. 10. 2015
36. Prof. dr. Philippe Mendels, Laboratoire de Physique des Solides, Universite Paris – Sud 11, Orsay, France, 16.12. – 18.12.2016
37. Prof. dr. Fabrice Bert, Laboratoire de Physique des Solides, Universite Paris – Sud 11, Orsay, France, 16.12. – 18.12.2016

# STAFF

**Researchers**
1. Asst. Prof. Tomaž Apih
2. Prof. Denis Arčon*
3. Asst. Prof. Zoran Arsov
4. Prof. Vid Bobnar
5. Prof. Janez Dolinšek*
6. Dr. Cene Filipič
7. Dr. Alan Gregorovič
8. Abdelrahim Ibrahim Hassanien, B. Sc.
9. Dr. Peter Jeglič
10. Dr. Martin Klanjšek
11. Dr. Tilen Koklič
12. Dr. Georgios Kordogiannis
13. Prof. Samo Kralj*
14. Prof. Zdravko Kutnjak
15. Dr. Mojca Urška Mikac
16. Asst. Prof. Aleš Mohorič*
17. **Prof. Igor Muševič*, Head**
18. Dr. Matej Pregelj
19. Asst. Prof. Miha Ravnik*
20. Prof. Maja Remškar
21. Prof. Igor Serša
22. Asst. Prof. Miha Škarabot
23. Prof. Janez Štrancar
24. Asst. Prof. Uroš Tkalec*
25. Dr. Polona Umek
26. Dr. Herman Josef Petrus Van Midden
27. Asst. Prof. Andrej Vilfan
28. Prof. Boštjan Zalar
29. Prof. Aleksander Zidanšek
30. Dr. Andrej Zorko
31. Prof. Slobodan Žumer

**Postdoctoral associates**
32. Dr. Franci Bajd
33. *Dr. Andreja Eršte, left 01.09.15*
34. Dr. Maja Garvas
35. Dr. Anton Gradišek
36. Dr. Jerneja Milavec
37. Dr. Giorgio Mirri*
38. Dr. Maryam Nikkhou
39. *Dr. Nikola Novak, left 01.07.15*
40. Dr. Stane Pajk*
41. Dr. Rok Podlipec
42. Dr. Brigita Rožič
43. Dr. Anna Ryzhkova
44. Dr. Iztok Urbančič
45. Dr. Jernej Vidmar*
46. Dr. Stanislav Vrtnik
47. Dr. Erik Zupanič

**Postgraduates**
48. *Dr. Goran Casar, left 01.06.15*
49. *Dr. Olga Chambers, left 01.07.15*
50. Matjaž Gomilšek, B. Sc.
51. Urška Gradišar Centa, B. Sc.

52. Dr. Matjaž Humar
53. Uroš Jagodič, B. Sc.
54. Tilen Knaflič, B. Sc.
55. Primož Koželj, B. Sc.
56. Mitja Krnel, B. Sc.
57. Marta Lavrič, B. Sc.
58. *Dr. Ajasja Ljubetič, left 15.02.15*
59. Janez Lužnik, B. Sc.
60. Bojan Marin*, M. Sc.
61. Aleksander Matavž, B. Sc.
62. Luka Pirker, B. Sc.
63. Gregor Posnjak, B. Sc.
64. Andraž Rešetič, B. Sc.
65. Muhammad Saqib, B. Sc.
66. Melita Sluban, B. Sc.
67. Jan Šömen, B. Sc.
68. Maja Trček, B. Sc.
69. Ana Varlec, B. Sc.
70. Maruša Vitek, B. Sc.

Technical officers

71. Dr. Luka Drinovec*
72. Dr. Andreja Jelen
73. Dr. Andraž Kocjan
74. Ivan Kvasić, B. Sc.
75. Jože Luzar
76. *Dr. Giorgio Mirri, left 01.11.15*
77. Dr. Griša Močnik*

Technical and administrative staff

78. Dražen Ivanov
79. Janez Jelenc, B. Sc.
80. Maša Kavčič
81. Davorin Kotnik
82. Sabina Krhlikar, B. Sc.
83. Silvano Mendizza
84. Janja Milivojević
85. Iztok Ograjenšek
86. Ana Sepe, B. Sc.
87. Marjetka Tršinar

Note:
* part-time JSI member

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