At the Department of Physics in the University of Jyväskylä, we investigate the basic phenomena of nature and educate future physicists and physics teachers.

Our Department is the most eminent research unit in Finland in the field of subatomic physics, i.e. particle and nuclear physics. Our Accelerator Laboratory is one of the largest and most international research infrastructures in Finland. The four accelerators housed by the laboratory are used to study nuclei and the structure of matter.

Our Department also specializes in studying matter on the scale of a nanometre. The modern instruments for this research can be found from the Nanoscience Center, located next to the Department and housing part of our personnel. Our Department is highly international and we collaborate with numerous universities and research institutes abroad, such as CERN.
HEADING OF DEPARTMENT

FOREWORD

This Annual Report provides an extensive summary of the activities at the Department of Physics during the year 2019. According to the valid strategy of the Department of Physics, the research carried out at the Department covers two main areas, subatomic physics and materials physics, both encompassing a body of experimental and theoretical research topics. The former includes nuclear physics, particle physics, and cosmology while the latter includes nanophysics and applied materials physics. Experimental research into nuclear and particle physics is carried out in the Accelerator Laboratory and in several major European research centers. Nanophysics is mainly studied within the interdisciplinary Nanoscience Center. Subatomic physics and multidisciplinary nanophysics are among the core research areas of the Faculty, and continue being subjects of several profiling actions carried out by the University.

During the year 2019 the scientific activity of the Department remained at a high level. The total amount of publications produced was about 300. Active international collaborations as well as national alliances, especially with Helsinki Institute of Physics, have significantly contributed to the results achieved. In addition to the mainstream academic research, the Department has continued its activities in applied research and industrial collaborations. Especially, the Radiation Effects and Industrial Applications group, lead by professor Ari Virtanen (retired at the end of year 2019) continued and extended its active collaboration with major European and global space organizations and industries.

In spite of the strong emphasis put on the development of teaching practices and curriculum and on increasing the attractiveness of physics among high-school, the resilient tendency of a declining number of new students still seems to prevail. The Department is committed to continue and increase its efforts to reverse this development in the coming years.

Personal achievements and highlights of the year include the national award for the best Masters Thesis to Emmi Kirjanen. Also worth mentioning is the appointment of Senior Researcher Juha Uusitalo as a Visiting Professor at the University of Liverpool, in recognition of his outstanding leadership in the spectroscopy of exotic nuclei. Noteworthy are also the two honorary doctorates awarded in the Tenth Conferment of Degrees Ceremony for the University to two distinguished physicists, Academician Risto Nieminen (Professor Emeritus at Aalto University) and Professor Peter Butler (University of Liverpool), who both have had a marked contribution to the development and success of also this Department.

During the year 2019 the personnel of the Department was still in the state of rapid change as the long-time members of the personnel Professor Ari Virtanen, Senior Lecturer Sakari Juutinen and Laboratory Engineer Raimo Seppänen retired, and Professor Jan Rak resigned and moved on to new duties. On the other hand, two new Senior Lecturers, Panu Ruotsalainen and Sami Räsänen as well as Laboratory Engineer Jukka Jaatinen and Staff Scientist Panu Ruotsalainen and Sami Räsänen as well as Laboratory Engineer Jukka Jaatinen and Staff Scientist Jan Sarén were engaged. We are happy to note that Professor Virtanen and Senior Lecturer Juutinen will both continue their contribution to the activities of the Department under Emeritus status.

After several difficult years caused by declining core funding and fluctuating external funding, the financial status of the Department improved notably during the year 2019, the final result being slightly positive. This was mainly due to success in external funding as several research groups and individual researchers were very successful in applying for competitive long-term funding both from national and EU sources. This will contribute in stabilizing the financial situation of the Department also in the coming years, and is another clear indication of the high quality of the work of the entire personnel.

Markku Kataja
HEAD OF DEPARTMENT

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51 The Department has produced an annual report every year since 1976. The reports since the year 2000 are available in electronic form in: https://www.jyu.fi/science/en/physics/current/annual-reports
SOME STATISTICAL DATA FROM 2019

145 PERSONNEL

Professors incl. associate professors 18
Senior lecturers and researchers 34
Postdoctoral researchers 27
Doctoral students 36
Technical staff 30
ERC grantees 3
Academy professors 1

+ Several research assistants (MSc students)
Personnel counted in man-years

362 UNDERGRADUATE STUDENTS
of which new students 47
Doctoral students 69

21 BSC DEGREES
30 MSC DEGREES
15 PHD DEGREES

310 NUMBER OF FOREIGN VISITORS
418 IN VISITS

256 Peer reviewed publications
32 Conference proceedings
6 Other (articles in books etc.)

CONFERENCE AND WORKSHOP CONTRIBUTIONS
Invited talks 148 | Other talks 108 | Posters 50

14.3 FUNDING (million €)

- Basic financing 8.2
- Sales (contract research) 0.9
- Income according to separate laws (mainly EU funding) 1.8
- Government grants (Academy of Finland, Business Finland, other government grant) 3.4
- Other income 0.1

In addition, the Department received 0.7 M€ for research infrastructures.

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Editor
Pekka Koskinen, Minttu Haapaniemi
Cover picture
Sami Malola, University of Jyväskylä
THE YEAR 2019 AT THE NSC

Tero Heikkilä

During 2019, the emphasis of Nanoscience Center’s activities was on planning the future. In April, we had a common two-day meeting WeNSC in Konnevesi research station, after which our distinguished International Advisory Board (IAB) gathered to the NSC to evaluate our activities and give recommendations for the future. The IAB found NSC’s focus areas well-structured and organized and capable of significant scientific accomplishments. Especially it applauded the positive atmosphere of the center, and the recent efforts for promoting interdisciplinary collaborations within NSC. In addition, it recommended improving and extending NSC’s infrastructure and putting more emphasis on student recruiting. We take these recommendations seriously and have already taken some steps to follow them.

Both the WeNSC and the IAB meetings contributed to setting up an NSC strategic plan that was released as a brochure and can be found both in the NSC web pages and in the NSC lobby. The plan expresses NSC researcher’s vision on building understanding of the nanoscale processes with multi- and interdisciplinary approaches, and mission to provide an environment for world-leading research, to educate multi-disciplinary experts and to communicating our findings to the science community and to the public. It also identifies several grand challenges motivating our research work, a list of near-term strategic aims within the center, and communicates our value base of fostering a culture of low hierarchy, promoting strong researcher identities and providing equal opportunities. While often such plans may seem clear and straightforward to an outside reader, they are not easy to write, as the process of devising such a plan requires making difficult choices of what to state and what not. I hope that our plan will be considered as a map aiding an ongoing discussion of our future role inside the university, research community and society – but a map that can be continuously updated as new roads are constructed and new connections are found into the previously uncharted territories where research takes us.

The NSC yearly newsletter (also found at NSC web pages and in the lobby) highlights the many events we organized in 2019, and the new research projects awarded to the center. Just to pick a few, I could mention the new ERC Starting Grant of Juha Muhonen for quantum technology, and the Business Day organized in November 2019 (at the same time as the Slush event in Helsinki). The latter gathered 16 companies and about 110 participants to bring together companies with students and to educate the companies about the research done in the whole Ylistönrinne where majority of the Faculty of Science and Mathematics is located. The experiences on this event were positive and we will likely make it a yearly event but organize it rather during early spring.
THERMAL NANOPHYSICS

Professor Ilari Maasilta

The group is one of the main users of the nanoscience center (NSC) nanofabrication infrastructure, and has currently three main research directions:

- Nanoscale thermal transport, especially focusing on phononic crystals and near-field transport
- Development of superconducting materials and devices, especially ultrasensitive superconducting radiation detectors and superconducting tunnel junctions

Utilizing novel nanofabrication and imaging techniques for interdisciplinary projects, such as nanoscale biological imaging with helium ion microscope (HIM) and 3D laser lithography.

www.jyu.fi/physics/materials/thermal-nanophysics

NANOSCALE THERMAL TRANSPORT

We continue to have a strong focus on the theory and experiments of nanoscale thermal transport. In 2019, we obtained new record-breaking results with two-dimensional phononic crystals, made from hole arrays in thin SiN membranes. We studied, whether our previous unusual observation, that thermal conductance is reduced when the period and thus the dimension of the narrowest point is increased, has experimental limits [Tian2019]. Indeed, we found out that there was an optimal period ~10 µm with the highest record-low reduction, after which the conductance started increasing again. This was successfully modeled as a crossover from the coherent to the diffusive limit, where boundary scattering from the hole edges started to dominate.
DEVELOPMENT OF SUPERCONDUCTING DEVICES AND MATERIALS

Our group’s role in the collaborative EU FET project SUPERTED developing a novel superconducting-ferromagnetic thermoelectric radiation detector increased during 2019. As an example, we performed a numerical analysis, demonstrating how the novel detectors can be read out with superconducting SQUID-amplifiers [Geng2019], without much degradation of the detector characteristics.

New collaboration partners in the area of superconducting devices are the National Institute of Science Education and Research (NISER) in India and Cambridge University in the UK. Together with those institutes, we studied how magnetic domain walls in a ferromagnetic Ni film induced a modulation of superconducting properties in Nb/Ni bilayer stripes [Bhatia2019].

Collaboration with the accelerator-based materials physics group also continued in the area of using superconducting transition-edge sensor (TES) detectors with particle-induced X-ray emission (PIXE) spectroscopy. The most recent results demonstrated a novel setup, where PIXE measurements can be performed in air, in contrast to the usual vacuum conditions. This allows experiments on delicate or large size samples [Käyhkö2019].

In collaboration with biologists, we continued studies of bacteriophages. We investigated how different surfaces and surface treatments affect the antibacterial efficiency of a bacteriophage-loaded surface against a bacterial fish pathogen [Leppänen2019]. The conclusion was that a surface that does not bind the phages too strongly, so that it can release them into water, is the most effective.

NOVEL NANOFABRICATION AND IMAGING TECHNIQUES FOR INTERDISCIPLINARY PROJECTS

In the area of developing novel nanofabrication techniques, we recently showed that direct laser writing (3D lithography) can be used in a novel way: to fabricate metallic wires on 3D topography (using a positive resist and lift-off) [Heiskanen2019]. This is practically impossible with standard 2D lithography techniques, which require a flat substrate. The new technique can be utilized in experiments on 3D phononic structures.


The Molecular Technology group studies primarily the experimental electronic and mechanical properties of carbon nanotubes (CNTs) and devices that are based on them. The interests include both fundamental and applied aspects of CNT science and technology. The research in the group has extensively explored the basic electronic transport properties of high quality multiwalled carbon nanotubes (MWNT). Another important topic is the functionalization of CNTs with molecular species, whereby molecular complexes are formed.

www.jyu.fi/physics/materials/molecular-technology

Our studies on CNT-based molecular complexes, especially on CNTs solubilized in water with hemicellulose (xylan) has continued. Previously we investigated the transport properties of thin films casted from such very stable water based dispersions of CNTs [1]. Presently we are interested in exploring experimentally at the molecular level the character of the CNT/xylan complexes. This is pursued in collaboration with the Scanning probe group at the KU Leuven in Belgium.

We collaborated with the group of Prof. Matti Haukka, who does research on new chemical techniques for the benefit of the expanding 3D printing industry. Their project was to use selective laser sintering 3D printing to fabricate highly porous carbonous electrodes. The electrodes were prepared by using a mixture of fine graphite powder and a polymer powder (e.g. polystyrene) as the printing material. In other words, an electrical composite in which the graphite was the conducting material. We studied the percolation threshold of such composites within the framework of the BSc Thesis work of BSc student Joonas Jokivartio. The results are shown in figure 1 and were published in Ref. [2].


← Figure 1. Conductivities at room temperature of the 3D printed polystyrene and polyamide electrodes as a function of the graphite concentration.
MOLECULAR ELECTRONICS AND PLASMONICS

Associate Professor Jussi Toppari

Group studies nanoelectronics, -plasmonics, and -photonics, concentrating on phenomena involving molecules as active components or as building blocks. We continue developing our long experience on self-assembled DNA structures, like DNA origami, and their utilization in fabrication of electrical and plasmonic nanodevices [1]. We also study intensively a strong coupling between confined light, like surface plasmons and cavity photons, and molecules, concentrating on a new field polaritonic chemistry explained below [2,3]. Other topics include utilization of plasmonics to enhance the emission of fluorescent proteins for bioimaging, improving surface enhanced Raman spectroscopy (SERS) [4], as well as studying plasmonic properties of graphene.

The year 2019 has been a year of collaboration since many of the group’s international co-operative efforts, some even long standing, achieved significant results. These include for example plasmon-enhanced DNA-based detection of pathogens together with Prof. Wolfgang Fritzsche (IPHT, Jena, Germany) [5], surface passivation of nano-textured flexible silicon solar cell together with Prof. Timo Sajavaara from accelerator lab and Prof. Vamsi Komarala (IIT, Delhi, India) [6] and Identifying yeasts by SERS together with Prof. Vesa Hytönen (University of Tampere) and Jin Wang (Chinese Academy of Sciences, Hefei, China) [7].


TRACKING POLARITON RELAXATION FOR POLARITONIC CHEMISTRY

Under normal conditions molecules are always surrounded by an electromagnetic vacuum field. But, since all photonic modes are available and coupling to them is weak, they can be neglected. The situation is different for molecules within a confined light mode, since the confinement restricts the number of photonic modes available and enhances the light-matter interaction. In a strong coupling limit this leads to hybridization between photonic and molecular degrees of freedom, and formation of new light-matter states, polaritons, manifested by a splitting of the absorption spectrum into two peaks separated by the Rabi splitting. The hybridization into polaritons delocalizes the excitation over many molecules and also changes their potential energy surface. Thanks to this, coupling molecules to confined light modes is showing a great promise for manipulating chemistry.

To effectively manipulate photochemistry with confined light, the molecules need to remain in the polaritonic state long enough for the reaction to complete fully on the modified potential energy surface. To understand what determines this lifetime, we – together with the group of chemistry professor Gerrit Groenhof – have performed atomistic molecular dynamics simulations of room-temperature ensembles of rhodamine chromophores strongly coupled to a single confined light mode with a 15 fs lifetime. The results of the simulations suggest that the lifetimes of the optically accessible lower and upper polaritons are limited by:

• Ultrafast photoemission due to the low cavity lifetime
• Reversible population transfer into the “dark” state manifold.

Dark states are superpositions of molecular excitations but with much smaller contributions from the cavity photon, decreasing their emission rates and hence increasing their lifetimes.
We find that population transfer between polaritonic modes and dark state is mainly determined by the overlap between the polaritonic and molecular absorption spectra. Importantly, contrary to the common conception of “one-way” relaxation, excitation can also be transferred “upward” from the lower polariton into the dark-state reservoir. Our results suggest that polaritonic chemistry relying on modified dynamics taking place within the lower polariton manifold requires cavities with sufficiently long lifetimes and, at the same time, strong enough light-matter coupling strengths to prevent the back-transfer of excitation into the dark states.


HYBRID QUANTUM TECHNOLOGIES IN SILICON

Associate Professor Juha Muhonen

The development of quantum technologies is expected to revolutionize sensor applications and communication as well as lead to the actualization of a quantum computer. In our group we develop quantum components using silicon, the material that is already ubiquitous around us in computers, mobiles and all everyday electronics and hence provides unique possibilities for integrating the quantum components with existing photonic or electronic circuits. The motivation for our research is both in enabling practical quantum sensors and quantum computing components of the future and in probing fundamental physics in these on-chip quantum physics testbeds.

www.jyu.fi/quantum-technologies

SNAPSHOTS FREEZING A NANOSWING

In this work that was published as an Editor’s Suggestion in Physical Review Letters [1] we and co-workers from the AMOLF institute in Netherlands demonstrated fast pulsed measurements of a nanomechanical resonator, with accuracy close to the limits set by quantum mechanics. The experiments were performed at AMOLF.

One can imagine the experiment as a way to cool down a nanoswing. A swing in the playground will hardly move until someone gives it a push, but a nanosized swing (or a nanomechanical resonator in the jargon) is always moving due to random thermal vibrations. Thus, if one wants to accurately predict the swing’s position at any point in time, thermal motion needs to be eliminated and hence one needs to cool the swing near the absolute zero temperature. In this work, we developed a different approach by using laser light to take accurate and almost instantaneous measurements (snapshots) of the position of the nanoscale structure. We can do these measurements much faster than the time it takes for the nanoswing to interact with its thermal environment and hence after the measurement we have a reduced uncertainty in the swings position, similarly as if we had cooled the environment down.

Our nanoswing is a small silicon double rod that vibrates like a string and which is designed to interact strongly with the laser light that we use to measure its position. It is this strong interaction that allows us to perform the snapshot measurements instead of a conventional time-averaged measurement, which was the crucial step for this experiment. In the future both the structure and the methods developed could be used for quantum sensing applications.


↑ Doctoral students and the PI pretending to be aligning the laser for the homodyne interferometer.
COMPLEX MATERIALS

Professor Markku Kataja

The research scope of the group includes heterogeneous materials, theoretical and numerical modelling, complex fluid mechanics and rheology, X-ray tomography and 3D image analysis, as well as their applications in various industrial problems. The group runs an extensive X-ray Tomography Laboratory that includes three X-ray scanners used in non-invasive three-dimensional imaging and analysis of the internal microstructure of a wide range of heterogeneous materials. The research topics of the group include also statistical characteristics of random packings of elongated particles, structural analysis related to development of new bio-composites, complex flow dynamics and transport in heterogeneous materials.

www.jyu.fi/physics/materials/complex-materials

IN-HOUSE BUILT MICROTOMOGRAPH

The increasing demand for a powerful microtomographic device capable of imaging larger samples in a shorter time has lead the X-ray tomography laboratory (XTL) to design and construct a specially built microtomography device at the XTL. The device consists of a microfocus X-ray source (40 – 150 kV, 75 W), a flat-panel detector (15 x 11 cm, 7 MP), three linear stages and a rotary stage (Fig. 1). Control and reconstruction software development has also been carried out at the XTL. Samples of diameter 0 – 100 mm can be imaged with the corresponding resolution in the range 5 – 40 µm. The very first images taken with the device were of good quality (Fig. 1). The device will be fully operational after placing it into a radiation cabinet during the spring 2020. The device facilitates non-standard imaging and calibration procedures required for accurate measurements, but which often cannot be implemented with commercial devices.
MONITORING MECHANICAL EVOLUTION OF BENTONITE USING X-RAY IMAGING

Bentonite is a natural clay that has many unique properties such as ability to swell, and low permeability to water and other substances. For this reason it is planned to be used as a sealing material between spent nuclear fuel canisters and the bedrock in many nuclear waste repository concepts. However, bentonite has turned out to be a very complex material that poses severe challenges to modelling. Therefore, accurate experimental data on the hydromechanical behavior and transport properties of bentonite are needed. In this study, non-invasive X-ray imaging technique and numerical image analysis has been used to measure deformation and homogenization of various bentonite materials in a closed volume with initial void space. Compacted cylindrical bentonite samples ($d = 20$ mm, $h = 10$ mm), doped with tracer particles, were placed into sample holders where they were wetted and let to freely expand 4 mm upwards (Fig. 2). The swelling process was monitored by taking X-ray images of the sample and measuring the swelling pressure at both ends of the sample holder. The comprehensive study consisted altogether of 30 experiments where the initial dry density of the sample and the salinity and composition of wetting solution varied. In addition, three different types of bentonite material were tested. The duration of an experiment was 16 days and included total of 10 X-ray imaging sessions. Numerical image analysis is based on a tracer particle tracking algorithm and pixel specific values of X-ray attenuation coefficient calibrated to yield local solid and water content of the bentonite. The analysis yielded temporal evolution of the spatial distribution of swelling induced displacement and partial densities of both bentonite and water (Fig. 2).

Figure 2. A schematic cross-sectional view of the sample holder used in bentonite experiments (left) and an example of the results: the partial densities of bentonite and water at three instants of time (right).
MULTISCALE MODELLING OF HETEROGENEOUS COMPLEX FLUIDS

We develop a multiscale modeling scheme for numerical studies of complex fluids composed of immiscible phases. Such fluids are generally characterized by distinct spatial and temporal scales associated with the observable macroscopic flow behaviour and the mesoscopic phenomena related to underlying heterogeneities. Practical examples of this type heterogenous complex fluids include e.g. liquid-particle suspensions, colloids, aerosols and bubbly flows. The multiscale approach is based on concurrent coupling of a macroscale continuum model with mesoscale quasicontinuum simulations used to find the macroscopic intrinsic stress. In particular, the mesoscale simulations either replace completely the rheological macroscale rheological modeling or are used to determine locally the parameters of the assumed material model. The approach also aims in reducing the simulation time and simplifying the mesoscale simulation set-up. These are obtained by affecting the model coupling by choosing suitable frame of references for the mesoscale simulations and by applying sparse sampling simulation grids and interpolation of the material parameters whenever possible. Simulation time is also reduced by collecting and utilizing the previous mesoscale simulation results for local macroscale stress tensor whenever macroscale state parameters are previously surveyed and data exists. The feasibility of the approach was previously studied by solving flow of a wet foam in one-dimensional and in two-dimensional channel flows, by utilising DySMaL foam model in the mesoscale simulations. At the moment we study another implementation of the scheme where a dissipative particle dynamics (DPD) simulation has been utilized at mesoscale. In the previous studies only one macroscale state parameter, the velocity gradient tensor, was used to initialize the mesoscale simulation. In the present work we apply the method in a system described by two dynamic parameters, the velocity gradient tensor and the fluid density. The method in general is potentially useful for solving flows of complex fluids for which the observable macroscopic properties may be strongly affected by their heterogeneous mesoscopic scale structure.

IMAGING AND ANALYSES OF BIORESIDUAL CONCRETE

The research collaboration "Sustainable bioresidual concrete" including the faculty of information technology (FIT) and the Jyväskylä university of applied sciences (JAMK) considers environmental issues of technologies related to using concrete as a building material. The research includes development of mathematical modelling of concrete that contains bioresiduals such as soda ash from pulp mills. Several samples of bioresidual concrete were imaged with Skyscan 1172 microtomography device at XTL and the 3D images were analysed to yield porosity and pore size distributions. The data was used at FIT to construct a simulation model of concrete with realistic material properties [1].

We investigate physical and chemical properties of various nanosystems using computational techniques based on density functional theory, dynamical simulations and artificial intelligence. Our current main interest is to understand physical, chemical, catalytic and bio-compatible properties of atomically precise, ligand-protected metal nanoclusters and their self-assemblies. These “hybrid” well-defined nanoparticles constitute novel nanomaterials with potential applications in plasmonics, catalysis, biological imaging, sensing, and drug delivery. Our group interacts with several computational and experimental groups in Finland and around the world.

www.jyu.fi/science/en/nanoscience-center/research/nanoclusters

ARTIFICIAL INTELLIGENCE HELPS TO PREDICT HYBRID NANO PARTICLE STRUCTURES

Nanometre-sized hybrid metal nanoparticles have many applications in different processes, including catalysis, nanoelectronics, nanomedicine and biological imaging. Often it is important to know the detailed atomic structure of the particle in order to understand its functionality. The particles consist of a metal core and a protecting layer of molecules. High-resolution electron microscopes are able to produce 3D atomic structures of the metal core, but these instruments cannot detect the molecular layer that consists of light atoms such as sulfur, phosphorous, carbon, nitrogen and oxygen. Reliable information about the atomic structure of the interface between the metal and the molecular layer is crucial to build atomistic models for simulations of structure-function relations.
Recently, we demonstrated that it is possible to build a distance-based algorithm that "learns" to predict binding sites of molecules at the metal-molecule interface of hybrid nanoparticles by using already published experimental structural information on nanoparticle reference systems (Fig. 1) [1]. The algorithm can also rank the predicted structural models based on how well the models reproduce measured properties of other particles of similar size and type. The algorithm can in principle be applied to any nanometre-size structure consisting of metals and molecules provided that some structural information already exists on the corresponding systems.

Artificial intelligence and machine learning are often connected to "big data", and a relevant question is how many known nanoparticle structures are needed as reference in order to predict new structures? Our work implies that only a few dozen known structures are needed. The reason lies in the fact that the atomic structure or the metal-molecule interface is dictated by chemical bonding of mainly covalent type, meaning that only a discrete number of bond lengths and bond directions make chemical sense.

We are currently building efficient atomic interaction models for hybrid metal nanoparticles by using machine learning methods and training data generated from molecular dynamics simulations with accurate forces from density functional theory (DFT). These models allow us to investigate the atomic dynamics of nanoparticles at a fraction of the computational cost of heavy DFT simulations, but at the level of DFT accuracy.

Our work is done in collaboration with the group of prof. Tommi Kärkkäinen in the JYU IT Faculty and is funded by the AIPSE research programme of the Academy of Finland (Novel Applications of Artificial Intelligence in Physical Sciences and Engineering Research) [2].


CONDENSED MATTER THEORY

Professor Tero Heikkilä

We study the quantum and classical phenomena in small electronic systems, with a focus on superconductivity, magnetism, topological matter and open quantum systems. Our approach is based on phenomenological low-energy theory of quantum systems. In each project we work in close collaboration with world-leading experimental groups, and our goal is both to predict observables and to find out the key elements underlying the previous measurements.

www.jyu.fi/physics/materials/condensed-matter-theory

FLAT-BAND SUPERCONDUCTIVITY IN 2D MATERIALS

When trying to increase the superconducting critical temperature of materials closer to room temperature, one promising direction is to concentrate on systems with flat electronic bands. Especially interesting are the two-dimensional graphene-based materials, twisted bilayer graphene and periodically strained graphene, which host approximately flat bands. We have shown [1] that conventional BCS theory well explains the experiments done in twisted bilayer graphene, where superconductivity with a critical temperature of 1 K was found. We have also shown [2] that the same theory predicts superconductivity with a much higher critical temperature in monolayer graphene, assuming one can strain graphene periodically strong enough.

MAGNETO- THERMAL EFFECTS IN SUPERCONDUCTOR/ FERROMAGNETIC INSULATOR JUNCTIONS

Magnetization dynamics becomes strongly coupled to thermal transport in spin-split superconductor-nanomagnet interfaces. We show [3] that this allows for Peltier-like cooling effects, where externally applied magnetic driving pumps heat current across the interface. Conversely, temperature differences result to a force acting on the magnetization of the nanomagnet.

OPEN QUANTUM SYSTEMS APPROACH TO MOLECULAR POLARITRONICS

Inspired by recent measurements made in Assoc. Prof. Toppari’s group, we constructed a model [4] for the optical response of a plasmon-molecule system. Our theoretical approach, based on methods of quantum optics, allows for the treatment of molecular vibrations as well as the plasmon polarization. As a result, we can express the response of such a polaritonic system in terms of the properties of individual molecules, which is relevant for light-controlled chemistry.
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ELECTRON-INDUCED MASSIVE JOSEPHSON-LIKE DYNAMICS OF MAGNETIC DOMAIN WALLS

The dynamics of magnetic domain walls under current injection have been studied both theoretically and experimentally for a few decades, but a full quantitative understanding between the two has not yet emerged. We constructed [5] a Keldysh path integral-based model for domain wall dynamics in the presence of a “vacuum” provided by the conduction electrons, allowing to treat the domain walls as emergent low-energy particles. We also found that besides a spin torque/force and a damping mechanism, in metallic ferromagnets electrons can provide a mass term that acts qualitatively differently from the traditional Döring mass of the domain walls. We showed how this extra mass term can lead to hysteretic dynamics analogous to that found in superconducting Josephson junctions with a high quality factor.

PROXIMITY EFFECT IN SUPERCONDUCTING HETEROSTRUCTURES WITH STRONG SPIN-ORBIT COUPLING AND SPIN SPLITTING

Singlet Cooper pairs can be converted into triplet ones and diffuse into a ferromagnet over a long distance in a phenomenon known as the long-range proximity effect (LRPE). This happens in materials with inhomogeneous magnetism or spin-orbit coupling (SOC). In this work, we consider a two-dimensional system with a large Rashba-type SOC and exchange field in the case where only one band is partially occupied. We developed [6] a generalized quasiclassical theory by projecting the Green function onto the partially occupied band (POB). We find that when the SOC energy scale is comparable with the exchange field, there is no LRPE. The reason is that the nonmagnetic impurities together with the large SOC and exchange field can effectively generate spin-flip scattering, which suppresses the proximity effect. We also show that when increasing either SOC or exchange field, the decay length of superconducting correlations can be significantly increased due to an approximately restored time reversal symmetry or spin rotation symmetry around the z (out-of-plane) axis.

QUANTUM MANY-BODY THEORY

Professor Robert van Leeuwen

The main focus of this group is to study quantum non-equilibrium systems and to develop the underlying theoretical tools and methods. The main approaches to non-equilibrium physics are Time-Dependent Density Functional Theory (TDDFT) and Nonequilibrium Green’s Function theory (NEGF). As an application the Green’s function method is applied to describe quantum transport through molecular devices.

www.jyu.fi/physics/materials/quantum-many-body-theory

CONTOUR CALCULUS FOR MANY-PARTICLE FUNCTIONS

In non-equilibrium many-body perturbation theory, Langreth rules are an efficient way to extract real-time equations from contour ones. However, the standard rules are not applicable in cases that do not reduce to simple convolutions and multiplications. We introduce an intuitive and graphical way for extracting real-time equations from general multi-argument contour functions with an arbitrary number of arguments.

This is done for both the standard Keldysh contour, as well as the extended contour with a vertical track that allows for general initial states. This amounts to the generalization of the standard Langreth rules to much more general situations. These rules involve multi-argument retarded functions as key ingredients, for which we derive intuitive graphical rules. We apply our diagrammatic recipe to derive Langreth rules for the so-called double triangle structure and the general vertex function, relevant for the study of vertex corrections beyond GW. [Hyrkäs 2019a]

As an application of the calculus rules, we have been able to show that the steady-state spectral function is a positive object at zero temperature - allowing for a probability interpretation also out of equilibrium - and which diagrammatic approximations that retain this nice feature. [Hyrkäs 2019b]

We are currently working on the generalization of these rules to the finite temperature case, as well as the transient regime. [Hyrkäs 2020]


We investigate low-dimensional nanomaterials, especially carbon nanomaterials, for their structural, mechanical, vibrational, electronic, and electromechanical properties using computational methods ranging from continuum to first-principles electronic structure methods.


Common two-dimensional (2D) materials have a layered three-dimensional (3D) structure with covalently bonded, atomically thin layers held together by weak van der Waals forces. However, recent experiments have suggested that even atomically thin 2D patches of metallic elements could be stabilized inside graphene nanopores. Motivated by such observations, we performed systematic density-functional studies on atomically thin elemental 2D metal films, using 45 metals in different lattice structures (Figure 1). Investigations of cohesive energies, equilibrium distances, bulk moduli, bending stiffnesses, interactions with graphene edges, and other related trends across the periodic table confirm many expectations but also reveal surprises [Nevalaita2018, Nevalaita2019]. In effect, metallic 2D structures turned out more stable than expected.


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Figure 1. Various criteria were investigated in order to arrange 45 metals in the periodic table according to their 2D stability in graphene pores. The most stable metals were found among late transition metals; the most stable candidate was found to be Cu.
SUPERCONDUCTING SPINTRONICS

Academy Research Fellow Mihail Silaev

We are a research theory group working on various topics in superconductivity, including the vortex physics, non-equilibrium and spin-transport phenomena usual and topological superconductors.


MOVING DOMAIN WALLS INDUCE LOSSES IN SUPERCONDUCTOR/FERROMAGNET HYBRID SYSTEMS

We have developed the theory [1,2] which describes how the superconductor can lose its fundamental property of having zero resistance in typical superconductor/ferromagnet device. This happens because of the induced magnetization dynamics in the attached ferromagnet. Although the force which drives the magnetization comes from the superconducting current, the system becomes inherently dissipative and in principle cannot sustain any amount of the superconducting current because of the voltage generated by the magnetization dynamics. We find the low-current resistance associated with the domain wall motion driven by the superconducting current. We suggest the finite slope of Shapiro steps as the characteristic feature of the regime with domain wall oscillations driven by the ac external current flowing through the junction. This work was done in collaboration with research group of drs. Irina and Alexander Bobkov and master student Daniil Rabinovich which from Moscow Institute for physics and technology.

IMPURITIES PROVIDE COUPLING OF SUPERCONDUCTING HIGGS MODE TO LIGHT

Recently the light-induced excitation of Higgs modes, that is oscillations of the order parameter amplitude in superconductors has been observed. The mechanism of this effect has remained not fully understood. In the absence of relaxation processes the order parameter amplitude is not affected by the irradiation since the systems of quasiparticle excitations and Cooper pairs move together and remain in the equilibrium with each other. Our work [3] demonstrates how the relaxation of quasiparticles by impurity scattering leads to the finite coupling between the Higgs mode and light. The suggested theory can be used in the future to study light-matter interaction in anisotropic and multiband superconductors such as high-temperature cuprates, iron pnictides and magnesium diboride.

↑ Figure 1. (a) Sketch of the system under consideration. Superconducting electrodes forming a Josephson junction are placed on top of a ferromagnetic strip. (b) A simplified model of the Josephson junction region with a Neel-type domain wall in the ferromagnetic interlayer.

European-wide public science event called Researcher’s Night was organized 4th time in the evening of 27.9.2019. More than 2,180 visitors gathered at the Department of Physics and attended the workshops, events, tours and lectures organized on a warm evening of late September. Additionally, 1,325 visitors were recorded at the Nanoscience Center, while the total number for the whole University exceeded 14,000.

Constant flow of people continued throughout the evening and even three hours weren’t enough for the visitors to see every event, just in our department alone. The Accelerator Laboratory had its open vaults installed with lights and plasmas. At the Pelletron accelerator, visitors got elemental analysis results on the fly from their valuables and MARA, IGISOL and RADEF groups presented their impressive tools, ions in motion and damage studies caused by cosmic particles, which visitors also could see by themselves at the cloud chambers. The tomography group had 3D visualizations, nuclear theorists helped children to build the isotope map of the valley of stability using Legos, and high energy physicists had a workshop where everyone could build a functional cloud chamber of their own.

At the Nanoscience center, physicists presented microfabrication examples, quantum computing chips, drove floating “cars” at the superconducting rails and gave presentations of clean rooms and devices used to make real science. The event contained lectures about “A measurement of time – towards a nuclear clock” and “The isotope factory of the University of Jyväskylä.” This year especially cosmology and high-energy theory groups had a successful night with plenty of visitors on their booths.

Thus, it again became evident that it is very important that all research groups take part to this type of public events. The main motivation of organizing public events like Researcher’s Night is the visibility gained and the long-term positive influence of the general public opinions about the science. This time the Physics Department also trialed a new kind of approach to gain better visibility in the main target group, i.e. 8-18 year old school children, who are also potential physics students of the future. The approach included a Youtuber with a science channel who was recruited to visit our department during the event – and as a result, successful Youtube videos gained more views than the department’s own material would ever have.

This year all groups were very active and innovative in coming up with new demonstrations. Particularly busy all evening were cosmology theoreticians, which triggered the Youtuber Petteri Mikkonen to dedicate a separate video on the cosmological questions his followers had sent him prior to the event. This type of “marketing” of the Physics Department will continue also in the future.

Mikko Laitinen
Responsible organizer of the Physics Department
Researcher’s Night 2019.
EMMA experiment visualized | Photo Władysław Trzaska

Ionizing Radiation visualized – Cloud chamber | Photo Mikko Rossi

Elemental analysis at Pelletron Accelerator | Photo Mikko Rossi

Ion Trap at IGISOL | Photo Władysław Trzaska
In 2019 the Accelerator Laboratory further consolidated its position as a forefront international user facility, providing reliable operations and a significantly high level of beam time and services to a wide range of research communities and commercial customers. The laboratory experienced many high points, with the successful completion of several long-term infrastructure projects and research highlights which are presented by the individual groups later in this report. The Accelerator Laboratory was also shocked and saddened by the loss of one of our much-loved members of staff, Jari Partanen (see below).

The remarkable run of successful FIRI funding applications (total funding 6.29 M€ from 2011–2019) unfortunately came to an end in January 2019, when the latest application did not receive funding. The year, however, saw a number of highlights with FIRI-funded projects being completed and put into the exploitation/production phase. Most notable of these was the commissioning of a cocktail of ion beams (up to $^{126}$Xe) with energies of 16.3 MeV per nucleon produced using the HIISI ion source and K130 cyclotron. The availability of this cocktail has already resulted in a significant increase in demand for beam time from the customers of the RADEF facility from the aerospace industries. The construction of the support structure for the JUROGAM3 array of germanium detectors (owned by the GAMMAPOOL consortium) was completed and the campaign of in-beam experiments at the MARA separator was begun.

Highly efficient use of the K130 cyclotron continued, with a total of 6421 beam time hours provided to 26 different research experiments and 17 periods of irradiations for industrial applications at the RADEF facility. Demand for beam time from the K130 cyclotron remains at the highest level in the history of the laboratory – in 2019 a total of 41 proposals were submitted to the Program Advisory Committee requesting 340 days of beam time for research. The number of beam time hours delivered to the RADEF facility for industrial applications increased to 1665 hours from the 1313 provided in 2018. This high level of service was even more remarkable considering that on the 2nd December, the laboratory began its first extended shutdown in almost 25 years. In order to overhaul the control system, no beam will be available for a total of three months. The control system upgrade was also funded via the FIRI instrument. The activities of the new H2020 RADIATE IA also started in 2019, resulting in increased demand for the ion-beam analysis facilities in the Pelletron laboratory and also new international users.

Funding from the EU and the Academy of Finland meant that several new positions could be filled. A Marie Curie Individual Fellowship was awarded to Ruben de Groot for his RAPTOR project, Kalle Auranen was awarded a Academy Post-Doctoral researcher position, and the receipt of Academy of Finland funding from the latest profiling call (Profi5) has meant that it has been possible to open a number of new positions. The first action to be taken was to name Anu Kankainen as Associate Professor in the new University Tenure Track system. Panu Ruotsalainen was selected to a position as Senior Lecturer, and Jan Sarén was selected as the first ever Staff Scientist in the whole University.

Again in 2019 there were some retirements of key figures who contributed greatly to the growth and status of the Accelerator Laboratory. The first of these was Senior Lecturer Sakari Juutinen who was one of the pioneers of in-beam gamma-ray spectroscopy and who retired after a career spanning over 30 years on 1st September. The second significant retirement was that of “Mr. RADEF” Professor Ari Virtanen, who is well-known for his forefront role in developing the activities of the RADEF group in providing services to industry and performing research into radiation effects in electronics.
These activities provide a significant contribution to the overall budget of the laboratory and Ari was recognized for his entrepreneurial skills with an award in 2011.

The Accelerator Laboratory was also honored to host a number of distinguished visitors, including H.E. Mr. Thomas Dodd, Ambassador of the United Kingdom to Finland, Minister of Economic Affairs Mika Lintilä and the leadership of the Academy of Finland. A further highlight was the award of an honorary Doctorate of the University of Jyväskylä to Professor Peter Butler FRS, in recognition of his key role in helping to develop the collaboration between the Accelerator Laboratory and the U.K. Nuclear Physics community and raising the profile of the laboratory.

Jari Partanen 1988–2019

The Accelerator Laboratory staff were deeply saddened by the passing of our young and highly talented Laboratory Engineer Jari Partanen, who lost his life in a road traffic accident on June 19th 2019 at the age of 31. Jari joined the Accelerator Laboratory around a decade ago as a summer student working in the Nuclear Spectroscopy group. Following this, he worked on his MSc thesis under the supervision of Juha Uusitalo and continued as a doctoral student playing a key role in the development of the new MARA separator. Jari’s contribution to the smooth start-up, commissioning and experimental campaigns of MARA cannot be understated. In 2015, a permanent position as a Laboratory Engineer supporting the Nuclear Spectroscopy and IGISOL groups became available and Jari was selected for the position. Jari’s expertise in designing electronics and control systems and his dedication to work were invaluable for the whole of the Accelerator Laboratory. Jari will be remembered for his sharp wit, unique sense of humour and strong Savo accent by all the staff of the Accelerator Laboratory who miss him greatly.
The main activities of the Nuclear Spectroscopy group are related to using in-beam gamma-ray and electron as well as decay-spectroscopic methods to examine the microscopic structure of the nucleus through studies of exotic nuclei, mainly along the proton drip line and in the region of heavy elements. The group is also active in international collaborations such as MINIBALL, IDS and ISS at ISOLDE, CERN, in the AGATA collaboration to build a gamma-ray tracking array and in the SUPER-FRS and HISPEC/DESPEC collaborations which form part of the NuSTAR pillar of FAIR in Germany. In 2019, our focus was on the first experimental in-beam spectroscopy campaign with the JUROGAM 3 Ge-detector array at the MARA separator. In total, 93 days of beam time were distributed to 12 separate experiments. The group members were co-authors in 29 peer reviewed journals and two conference proceedings.

www.jyu.fi/physics/accelerator/nuclear-spectroscopy

IN-BEAM SPECTROSCOPY ALONG THE N=Z LINE AT THE MARA SEPARATOR

Nuclei at and around the N=Z line are in focus for tests of fundamental symmetries of nature such as isospin symmetry and interactions which may act to break it. In addition, spatial overlap of neutron and proton wavefunctions in the N=Z systems gives rise to enhanced proton-neutron correlations whose significance in the isoscalar, T=0 channel is rather controversial. These physics questions are still largely un-ananswered since the available nuclear structure data specifically at the heavier end of the N=Z line is quite scarce.
Combining the MARA mass separator with JUROGAM 3 array in the beginning of 2019 opened a new door for the exciting in-beam studies of the $N=Z$ nuclei employing the recoil-beta tagging (RBT) method. First challenge was to identify excited states in the $N=Z$ nucleus $^{78}\text{Zr}$ for the first time. Although the usable beam time was cut short due to the beam and target related technical issues, we were still able to demonstrate the huge potential of RBT when employing mass-sensitive MARA separator – a clean recoil-beta tagged gamma-ray energy spectrum for $^{78}\text{Y}$ was produced within 2 days of beam time with similar statistics as measured earlier within 9 days of beam time with the RITU separator.

Figure 2. Gamma-ray energy spectrum obtained for $^{78}\text{Y}$ with the JUROGAM 3 array in conjunction with the MARA separator compared [bottom] with data obtained with JUROGAM 1 at the RITU separator [top].

† Figure 2. Gamma-ray energy spectrum obtained for $^{78}\text{Y}$ with the JUROGAM 3 array in conjunction with the MARA separator compared [bottom] with data obtained with JUROGAM 1 at the RITU separator [top].
Proof of principle test of lifetime measurements using charge plunger at MARA was performed. Isotopes of $^{180}$Pt and $^{178}$Pt were produced via 4$n$ and 6$n$ fusion evaporation channels, respectively, using $^{32}$S beam on $^{152}$Sm target. Although being challenging due to the relatively slow recoils, experiment successfully proved that the charge plunger method can be used for lifetime measurements.

**EXTERNAL RESEARCH**

The group members participated in the FAIR Phase-0 experiments that started in 2019. This included commissioning work of the upgraded setups such as Fragment Separator, in-beam tests of Super-FRS detectors and physics of superheavy elements. The isotope $^{289}$Fl (Flerovium) was studied through X-ray spectroscopy at the TASCA separator. In addition, collaborative efforts continued in SHE, DESPEC and Super-FRS Experiment collaborations of NUSTAR to shape the Phase-0 and Day-1 physics programmes of FAIR.

Due to the CERN long shutdown 2, ISOLDE activities in 2019 were mainly focussed on the analysis of earlier data. The main highlight was a discovery that will help with the search for electric dipole moments (EDM) in atoms and could contribute to new theories of particle physics such as supersymmetry. Short-lived isotopes of both radon and radium have both been identified as potential candidates for measuring EDMs in atoms. A MINIBALL experiment showed that the radon isotopes $^{224}$Rn and $^{226}$Rn vibrate between a pear shape and its mirror image but do not possess static pear-shapes in their ground states. In a paper published in *Nature Communications* [3], it is concluded that radon atoms provide less favourable conditions for the enhancement of a measurable atomic EDM than radium.

**MARA FOCAL PLANE STUDIES AND INSTRUMENT DEVELOPMENTS**

The lessons learned from the first RBT experiment at MARA provided an excellent starting point for the search of excited states in the $N=Z$ nucleus $^{94}$Ag for the first time. Careful investigation of the excitation function to optimize $^{90}$Ag yield required multiple changes of the beam energy and spent beam time, but the experiment ended in very positive atmosphere as two candidate gamma-ray transitions in $^{91}$Ag were identified. This finding has an important impact on testing the relevance of the spin-aligned, T=0 np pairing mode reported earlier for $^{92}$Pd.

Practically all known $N=Z$ systems in the A=70-80 mass region show relatively smooth rotational responses in comparison to their $N=Z+2$ neighbors, which demonstrate rather sharp backbendings already at fairly low angular momentum. The excited states in the $N=Z$ nucleus $^{84}$Mo have been previously assigned up to $J^*=10^+$, but the investigation of the delayed rotational alignments requires information on the excited states beyond the (tentatively) known $10^+$ state. Therefore, in 2019 an attempt was made to extend the level scheme in $^{84}$Mo. The $^{58}$Ni+$^{28}$Si reaction was used to produce $^{84}$Mo nuclei, which were then mass separated employing MARA. The JUROGAM 3 array was used to detect the emitted gamma rays, while the charged-particle detector JYtube was employed to suppress much stronger reaction channels involving evaporation of protons. During the data taking phase, some previously known coincident gamma-ray transitions in $^{84}$Mo were identified. This observation motivates a scrutinized offline analysis for the search of the new levels or just confirmation of the previously assigned ones.

**REFERENCES**

EXOTIC NUCLEI AND BEAMS

Professors Ari Jokinen and Iain Moore, Associate Professor Anu Kankainen, Academy Research Fellow Tommi Eronen, Senior Researchers Heikki Penttilä and Sami Rinta-Antila

The exotic nuclei and beams group exploits the universal ion guide production method at the IGISOL facility to explore short-lived exotic nuclei on both sides of the valley of beta stability. We use a novel combination of ion manipulation techniques, optical spectroscopy and a variety of nuclear decay spectroscopic tools to further our understanding of atomic and nuclear structure, nuclear astrophysics and fundamental physics.

https://www.jyu.fi/igisol

† Exotic nuclei and beams research group at IGISOL.
ON-GOING PROJECTS AND RESEARCH ACTIVITIES

Our group greatly benefits from the European Union’s Horizon 2020 research and innovation program. Projects and networks within ENSAR2, CHANDA and FET-OPEN as well as via the ChETEC Cost Action have supported our research activities. In 2019, the CHANDA project ended and was followed by two new EU EURATOM projects, SANDA and ARIEL. In SANDA (Supplying Accurate Nuclear Data for Energy and Non-energy Applications) Joint Research Activity, we have two tasks: to develop and verify a fission yield measurement technique based on the PI-ICR method at JYFLTRAP, and to design a large gas cell for IGISOL with electric field guidance. The ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning) transnational access project will provide support for external user experiments at IGISOL. Heikki Penttilä is the local coordinator of these EURATOM projects.

The European Research Council (ERC) Consolidator Grant project MAIDEN “Masses, Isomers and Decay studies for Elemental Nucleosynthesis” led by Anu Kankainen continued in 2019 with many essential experiments carried out at IGISOL. A Marie Curie Individual Fellowship was awarded to Ruben de Groote for RAPTOR, “RIS And Purification Traps for Optimized spectRoscopy”.

Research at IGISOL is also strongly supported by the Academy of Finland with two Academy Research Fellows and an Academy postdoctoral researcher working for nuclear astrophysics, neutrino physics, and laser resonance ionization, respectively. Additionally, FIRI funding from the Academy of Finland has been essential for renewing our research infrastructure. Our group is also leading the development and exploitation of the first phase of MARA-LEB at JYFL-ACCLAB, with an ongoing academy project led by Iain Moore.

We actively participate in international collaborations, performing research and development work at other facilities, including GANIL, ISOLDE (CERN) and GSI, the site of the future RIB facility FAIR. Many of our international activities were carried out in close collaboration with the Helsinki Institute of Physics. French collaborations were also strengthened with dual-doctorate (cotutelle) PhD students Marjut Hukkanen, jointly supervised with the University of Bordeaux, and Lama Al Ayoubi, jointly supervised with the Université Paris Saclay.

DEVELOPMENTS

Multinucleon-transfer reactions at IGISOL

Multinucleon-transfer (MNT) reactions have gained increasing attention as a promising way to produce neutron-rich nuclei beyond the fission fragment region. At IGISOL, a joint research activity together with researchers from GSI/FAIR, ELI-NP, and JINR-Dubna was initiated in 2018 to pursue MNT reactions at IGISOL. A proof-of-principle experiment took place in June 2019. The new HIISI ECR ion source was employed to produce a 945-MeV $^{136}$Xe beam, which impinged on a rotating $^{209}$Bi target mounted outside a helium-filled gas cell. An alpha spectrum stemming from the produced alpha-radioactive nuclei was successfully measured at the IGISOL focal plane (see Fig. 1) proving that the method works. The next step of the project is to optimize the efficiency of the setup by building a dedicated platform and gas cell for MNT reactions.

![Figure 1. Alpha spectrum measured for the $^{136}$Xe+$^{209}$Bi MNT reaction at A=211.](image-url)
Figure 2. The MR-TOF installation work in summer 2019.
Multi-Reflection Time-of-Flight mass spectrometer on its way to online commissioning

The Multi-Reflection Time-of-Flight (MR-TOF) mass spectrometer has been commissioned using an offline test bench and stable surface ion source. In summer 2019, the MR-TOF was installed in a modified beamline between the ion cooler-buncher and JYFLTRAP (see Fig. 2). The online commissioning will take place in 2020. The MR-TOF will provide a fast way to select ions of interest for mass measurements at JYFLTRAP or decay spectroscopy experiments at IGISOL. It can also be used for mass measurements as such.

RAPTOR

Many of the isotopes which can be (uniquely) produced at IGISOL have a challenging atomic structure, which means continuous developments are needed in order to reach the sensitivity required for their study. A new direction that is currently being pursued and supported through Marie Curie funding is the development of a low-energy, medium-resolution collinear resonance laser ionization setup, RAPTOR. By relying on resonant laser ionization, an improved efficiency will be achieved compared to standard collinear laser spectroscopy, while only moderately reducing the resolving power. First physics cases for the project are to extend measurements on the silver and palladium isotopic chains further from stability.

Offline characterization of the MARA-LEB gas cell

The first offline tests of the new MARA-LEB gas cell were performed using a radioactive $^{223}$Ra alpha-recoil source ($T_{1/2} = 11.4$ d) in the IGISOL target chamber (Fig. 3). Survival efficiency and evacuation time of ions transported by subsonic helium gas flow were studied. To ensure that the gas cell was clean, it was conditioned by baking with temperatures at about 100 degrees Celsius. A maximum ion survival efficiency of 12% and shortest evacuation time of about 100 ms were measured. A number of additional studies are scheduled for 2020, including tests with a beta recoil source for neutralization of recoils, as well as in-gas-cell and in-gas-jet laser ionization spectroscopy of tin isotopes. Moreover, the MARA-LEB gas cell is being characterized numerically in COMSOL Multiphysics software.

RESEARCH HIGHLIGHTS

Publication highlights

The beta-decay experiment on $^{20}$F performed at IGISOL in January 2018 revealed that the transition between the ground states of $^{20}$F and $^{20}$Ne is exceptionally strong. This finding helps to pin down the fate of intermediate-mass (around 7-11 solar masses) stars. The new experimental result increases the likelihood that the star is (partially) disrupted by a thermonuclear explosion rather than collapsing to form a neutron star. The results were published in Physical Review Letters [1] and selected as an Editor’s Suggestion accompanied with a Physics Viewpoint article.

Another Letter [2] published in 2019 focuses on the beta decay of the ground and isomeric states of $^{100}$Nb and $^{102}$Nb, resolved using the JYFLTRAP Penning trap, and sent for beta-decay intensity measurements using the total absorption gamma-ray spectroscopy technique. The studied nuclei are among the principal contributors to the reactor antineutrino energy spectrum. The new data have a large impact on antineutrino summation calculations and reduce the discrepancy between the summation model and reactor antineutrino measurements.

Successful test of the MONSTER spectrometer

MONSTER (Modular Neutron Spectrometer) is a new detector array for measuring beta-delayed neutrons and their energies (see Fig. 4). Originally designed for experiments at FAIR, it has been built within an international collaboration including groups from CIEMAT (Spain), VECC (India), JYFL/HIP (Finland), IFIC (Spain), and UPC (Spain). Data on beta-delayed neutrons are essential for nuclear astrophysics, nuclear structure physics and for more accurate simulations of nuclear reactors. In a landmark experiment at IGISOL, beta-delayed neutrons from $^{83}$As were used to test and characterize the performance of the MONSTER setup, which performed impeccably. The experiment also significantly improved the primary data for this particular decay mode, contributing to our understanding of nuclear structure. The prospects for new MONSTER experiments at IGISOL look bright!

Mass measurement highlights

The Phase-Imaging Ion Cyclotron Resonance (PI-ICR) technique has provided new possibilities for high-precision mass measurements of exotic nuclides at the JYFLTRAP Penning trap mass spectrometer. One of the first measurements with the technique was $^{88}$Tc [6]. In 2019, JYFLTRAP focused on neutron-rich isotopes of Ru, Rh and Ag. These nuclides typically have low-lying, long-living isomeric states, which have been impossible to resolve with the commonly used TOF-ICR technique. In addition, the three long-living isomeric states in $^{130}$In were resolved and measured for the first time, see Fig. 5. This provides more accurate mass values for the astrophysical rapid neutron capture process, and yields information on isomeric states and nuclear structure. In addition to the mass measurements, the PI-ICR technique has been employed for fission yield determination [7].
Lastly, in-source resonant ionization spectroscopy was performed on 96-104\textsuperscript{Ag} using a novel inductively-heated hot-cavity catcher ion source. In order to detect nuclei with very low production cross sections, the ion beam was purified with JYFLTRAP and the PI-ICR method was used to achieve nearly background-free ion counting. This combination afforded the study of 96\textsuperscript{Ag} produced in the reaction 14\textsuperscript{N}(92\textsuperscript{Mo}, 2p8n)96\textsuperscript{Ag} with an event rate of about one ion per 5 minutes. The dipole moment and charge radius of 96\textsuperscript{Ag} will provide a crucial benchmark for nuclear structure theory.

Selected publications


INSTRUMENTS AND METHODS IN NUCLEAR, PARTICLE, AND ASTROPARTICLE PHYSICS

Senior Researcher Władysław Trzaska

One of the most exciting aspects of experimental physics is doing what nobody has done before. Development of new instruments and methods is an integral part of that process. Over the past decades the activities of the HENDES group expanded from low-energy nuclear physics to relativistic heavy-ion collisions, neutrino physics, and ultra-relativistic cosmic rays. In addition to various spectrometers and devices for the use with cyclotron beams our group continues contributing to the design, construction and upgrade of the ALICE experiment at CERN, as described in the ALICE chapter of this Annual Report. The status of the Underground Physics is presented in the Neutrino and Astroparticle Physics. In this section, we concentrate on Nuclear Reaction studies carried out at the K130 cyclotron and in the other European facilities.

https://www.jyu.fi/hendes

*↑ Members of the Nuclear Reaction team during the August 2019 experiment at JYFL K130 cyclotron.*
One of the highlights of 2019 was experimental study of the influence of nuclear shells on fission of excited Hg and Sg nuclei. The goal of the run was to improve our knowledge of fission process in the regions of transactinide nuclei (superheavy nuclei) and confirm the recently observed asymmetric mass distribution for beta-delayed fission of $^{180}$Hg. This observation has provoked intensive studies of the fission properties of nuclei with Z < 82. The fission of trans-actinide nuclei is of special interest for the study of fission process connected with the investigation of influence of nuclear shells on the fission process of superheavy nuclei. Some of the unanswered questions include: are the fission properties the same as for actinide nuclei? what is the influence of shell structure on the formation of fission fragments?

The measurements were done in August and lasted two weeks. The modernized JYFL Large Scattering Chamber was equipped with a new version of the double-arm time-of-flight spectrometer CORSET allowing measuring mass distributions of fission fragments with accuracy of ±1.5u and to reliably separating fission from other competing binary processes taking place in these reactions. The compound nuclei of $^{176,180}$Hg (Z=80) and $^{264}$Sg (Z=106) were formed in the reactions $^{64,68}$Zn+$^{112}$Sn and $^{32}$S+$^{232}$Th. Each beam/target combination was measured at several excitation energies. The data analysis is ongoing but the first, preliminary results indicate that the fragment mass distributions of fission of $^{176,180}$Hg are asymmetric, even at the excitation energy of about 48 MeV. This observation agrees qualitatively with P. Möller’s predictions [P. Möller, J. Randrup and A. J. Sierk, Phys.Rev. C 85 024306 (2012)] for these nuclei. However, contrary to the theoretical prediction, the mass distribution for $^{176}$Hg is more asymmetric, in terms of peak-to-valley ratio, than $^{180}$Hg.

Nuclei made of clusters are essential for the study of nuclear matter. In that respect beryllium isotopes hold a special importance as there are reasons to believe that they may contain structures with multiple centers called dimers. The cluster configuration of such nuclei is manifested not only in their structure, but also in the mechanism of interaction with other light nuclei and is largely manifested in the characteristics of individual reaction channels (merging, transfer, inelastic scattering, etc.). The cluster states can be reviled through interaction in the form of exotic systems, such as: multineutrons, $^3$He, etc. We are happy to report that in February 2019 our work on “Manifestation of the cluster structure of $^9$Be nuclei in the mechanism of their interaction”, performed in Dubna and at JYFL by S. Lukyanov, A. Denikin, V. Maslov, M. Naumenko, Yu. Penionzhkevich, J. Mrazek, W.H. Trzaska, K. Mendibaev, N. Skobelev, and Yu. Sobolev was awarded the Second Prize in the field of Experimental Physics Research by the Jury of the 2018 JINR prize committee.

Selected publications:


T. Malkiewicz et al. (2019), Production of a $^{12}$C radioactive ion beam based on $^{18}$O(n, α), European Physical Journal A, 55 (6), 88. DOI: 10.1140/epja/2019-12761-y.


E.M. Kozulin et al. (2020), Features of the Fission Fragments Formed in the Heavy Ion induced $^{32}$S + $^{197}$Au reaction near the interaction barrier, European Physical Journal A, 56 (1), 6. DOI: 10.1140/epja/s10050-019-00019-5.
NUCLEAR STRUCTURE AND NUCLEAR PROCESSES

The nuclear-theory group of JYFL develops nuclear-structure models and applies them to topics of weak-interactions physics. The topics include neutrino-nucleus interactions at solar and supernova energies, rare weak decays like forbidden beta decays and double beta decays, nuclear muon capture and WIMP-nucleus scattering for direct dark-matter detection. The group is theory partner of the large underground experiments SUPERNEMO and COBRA and collaborates with experimental groups at JYFL, RCNP Osaka, etc. Theory collaboration with the JYFL FIDIPRO group and many other groups abroad is being pursued as well.


NUCLEAR MUON CAPTURE AND ITS RELATION TO NEUTRINOLESS DOUBLE BETA DECAY

A negative muon can be stopped at an atomic target where it can decay or can make its way down to the atomic K orbital and then be captured by the atomic nucleus [1]. This latter process is called the ordinary muon capture (OMC), being a process similar to the nuclear electron capture (EC). However, a notable difference between the two processes is the 200 times larger mass of the muon, about 106 MeV, compared with the mass of the electron, 0.511 MeV. Due to the large momentum exchange in the OMC, of the order of 50–100 MeV/c, the OMC can lead to nuclear final states which are both highly excited and of high multipolarity (J,p), where J is the angular momentum of a nuclear state and p its parity.

This momentum exchange is of the same order of magnitude as that of the neutrinoless double beta (0νββ) decay, where the exchange of a Majorana neutrino between two neutrons leads to the decay of a nucleus (A,N,Z) to its isobaric daughter (A,N-2,Z+2) through virtual nuclear states of the intermediate isobar (A,N-1,Z+1).

It has been proposed [2,3] that the OMC, when targeted to muon capture on the double-beta daughter nucleus (A,N-2,Z+2), and thus leading to states of the double-beta intermediate nucleus (A,N-1,Z+1), could be used as a probe of virtual transitions in the double beta decays (0νββ decay and the two-neutrino double beta, 2νββ, decay).

The first quantitative comparison of the 2νbb strength distributions (the transition amplitudes squared as a function of the excitation energy in the 0νββ intermediate nucleus) and OMC strength distributions was performed for light nuclei in [4]. There OMC was found to be a powerful probe of 2νββ decays, at least in light nuclei. Recently we have extended this comparison to 0νββ decays of medium-heavy and heavy nuclei [5].
The OMC-related research has recently experienced a boost through the advent of new experimental techniques and facilities, e.g. at RCNP (Research Center for Nuclear Physics) in Osaka, Japan, at PSI (Paul Sherrer Institute) in Willigen, Switzerland and at J-PARC (Japan Proton Accelerator Research Complex) in Ibaraki, Japan. A recent highlight of the OMC studies at RCNP and J-PARC is the achieved measurement of the OMC strength distribution in the nucleus $^{100}$Nb, following the OMC on the nucleus $^{100}$Mo. We have compared the extracted experimental distribution with the corresponding computed one in [6]. This is the first time when such a comparison has been performed, and it resulted in an almost perfect match between the two distributions, as shown in figure 1. Here a Lorentzian folding has been applied for easier comparison of the experimental and theoretical distributions. In case of the two theoretical curves the distribution made up by lower multipoles is separated from the distribution containing all the multipoles. A follow-up study of the OMC strength distributions in the intermediate nuclei of many $0\nu\beta\beta$ decays of experimental interest was achieved in [7].

A remarkable thing in the OMC strength distribution in figure 1 is the appearance of an OMC giant resonance at around 12 MeV of excitation energy in $^{100}$Nb. This resonance is mostly composed of multipoles $(1,-)$ and $(2,-)$ which consist of single-particle excitations between two oscillator major shells. The lower 7 MeV satellite resonance consists of the $(1,+)$ and $(2,+)$ multipoles, being built from single-particle excitations within one oscillator major shell.

FIDIPRO – GLOBAL PROPERTIES OF NUCLEI

Senior Researcher Markus Kortelainen

Our group develops and applies nuclear structure models, by mainly using the nuclear density functional theory as a theoretical framework. Our goal is to improve nuclear models and their description of the nuclei at the global level.


ISOBARIC MULTIPLET MASS EQUATION

The strong nucleon force follows approximately isospin symmetry. This means that the strength of the interaction is roughly similar between different nucleon species. There is, however, a small isospin symmetry breaking term in the strong force. Naturally, the Coulomb interaction provides another source of isospin symmetry breaking. The impact of isospin symmetry breaking can be seen in the energies of states along the nuclei on the same isobar. Due to broken isospin symmetry, these isobaric analog states no longer have the same energy. We have demonstrated that the energy differences between analog states can be explained well by introducing isospin symmetry breaking forces [1].

SMALL-AMPLITUDE COLLECTIVE MODES OF A FINITE-SIZE UNITARY FERMI GAS IN DEFORMED TRAPS

Studies of strongly interacting ultracold atomic gases have interdisciplinary interests in the quantum many-body systems, such as in condensed matter, nuclear physics, and neutron stars. The collective oscillation frequencies and damping rates of cold Fermi gases can be measured, which provides a good testing ground for various aspects of many-body theories. We have investigated collective breathing modes of a unitary Fermi gas in a deformed trapping potential [2]. These modes were computed by using superfluid linear response theory. When going from spherical trapping potential towards more elongated potential, a large shift in the resonance frequency was seen. Also, at the limit of large particle number, connection to the hydrodynamical result could be established.

↑ Figure 1. Spatial distribution of transition density in an elongated trap for a system of 200 particles. This figure was selected for Physical Review A’s November 2019 Kaleidoscope.


RADIATION EFFECTS

Professor Ari Virtanen

We are specialized in applied research around nuclear and accelerator based technology and operate the Radiation Effects Facility, RADEF, for the studies of radiation effects in electronics and related materials. RADEF officially became an ESA supported European Component Irradiation Facility (ECIF) in 2005. Since then we have carried out irradiation tests not only for ESA and the European space industry, but also for other world leading space organizations (e.g. NASA, JAXA, CNES), companies and universities. The contract with ESA was again renewed in 2018 for five years with an option of two last years.

https://www.jyu.fi/accelerator/radef

In addition to the old 9.3 MeV/n ion cocktail, used since 2005, a new 16.3 MeV/n cocktail became available to customers on January 2019, and even higher energy cocktail with 22 MeV/n is under development. These attractive cocktails were developed together with our ECR group, which was part of their very successful HIISI ion source project.

Commercial services used 1,299 hours of K130-accelerator beam time in 49 campaigns with 30 different companies, institutes and universities. This corresponds to approximately 20 % of the K130 beam time hours in 2019. The distribution of beam time between different users is shown in figure 2. The total revenue of RADEF (commercial, EU and ESA projects) in 2019 was over 1 M€.
RADSAGA

The project RADSAGA (RADiation and Reliability Challenges for Electronics used in Space, Aviation, Ground and Accelerators) has been going on since 2017 under coordination of CERN. RADEF group is one of the seven beneficiaries and has also been heavily involved in the management of the project. The project has, for the first time, brought together the European industry, universities, laboratories and test facilities at this scale, and will eventually educate 14 PhD’s on the subject of radiation related issues in electronics. Three of these students will graduate from JYFL, two hosted by RADEF and one by CERN. The project spans the years 2017–2021. This EU MSCA-ITN Horizon2020 project (GA#721624) was granted total of 3.9 M€.

Correlations of Direct Ionization Effects from Low-E Protons to Energetic Heavy Ions (ESR 1)

The general objective of this work is to study direct ionization effects of low energy protons and heavy ions. This includes numerical descriptions of the linear energy loss of protons and heavy ions per unit distance as well as the radial shape of the ionization track structure. The aim of this is to provide a numerical tool to estimate the sensitive volumes of microelectronics regarding single event effects from direct ionization. In addition, Monte Carlo simulations and time of flight (ToF) based LET measurements are used to validate the approach. Figure 3 illustrates the comparable performance of our energy loss model to other established models.

Figure 3: Percentage deviation of the modeled values to the experimental values (Oxygen ions in Aluminium) of a wide range of projectile kinetic energies.

Stuck Bits in SDRAMS (ESR 2)

When Synchronous Dynamic Random Access Memories (SDRAM) are irradiated they can suffer from what is known as stuck bits. When these bits are read, they always return the same value independently of what was written to them. This effect is a consequence of how the memory works, i.e. how the memory store a ‘1’ or a ‘0’. The cells in the memory contain a capacitor which, when the cell is storing a ‘1’, can be charged, and, when storing a ‘0’, can be discharged. Irradiation can cause the capacitor to be discharged by different mechanisms, or it can damage the cell so that the time a charge is stored on the capacitor is decreased. The time a cell can store a charge is called the retention time. In figure 4 the retention time of the cells in memories irradiated by a given number of ions is shown. Even if the data in the memory cells are refreshed with short time intervals, many cells fail to store the data after the memory has been irradiated. The data in the figure was presented at the RADECS conference 2019. The study of the effect of irradiation on SDRAMs and the creation of stuck bits in them is ongoing.

Figure 4: Retention time distribution of memory cells.
RELEVANCE, GUIDELINE AND TOOLS FOR RADIATION TESTING OF COMPONENTS AND SYSTEM TO BE USED IN COMPLEX ENVIRONMENTS (ESR 15)

The scientific research was devoted to studying the impact of singly charged particles induced Soft Errors on current Radiation Hardness Assurance practices. This included:

- The SEE pion resonance as opposed to other hadrons for the accelerator RHA;
- The proton direct ionization induced SEUs and their impact for the space RHA;
- The use of high energy electrons for displacement damage studies in place of protons or neutrons.

The technical research was devoted to writing guideline documents. This includes:

- The use of 14 MeV neutrons as an alternative for soft error testing to spallation sources;
- A first draft of the guideline for radiation testing of complex systems.

† Figure 5. Pion SEU resonance observed experimentally and reproduced numerically. It turns out the resonance is not that meaningful in the accelerator SER because the peak pion flux is above the resonance and the environment is thus dominated by neutrons.

† Figure 6. Proton direct ionization SEU cross section enhancement in the RADSAGA 65 nm SRAM. Simulations show that the SER in typical Low-Earth Orbit for this device would be dominated by proton direct ionization.

† Figure 7. Leakage current measurements on PIN diodes. The curve shows that electrons are twice less effective in inducing displacement damage than it was thought from previous studies. However, linearity with fluence make them suitable for displacement damage testing.
RADIATION EFFECTS IN SILICON CARBIDE POWER DEVICES

The focus of this project is the physical Single Event Effect (SEE) mechanisms leading to degradation and catastrophic failure of silicon carbide (SiC) power devices when exposed to different radiation environments. This work involves collaboration with CERN, ETH Zürich, Vanderbilt University, Helsinki Institute of Physics, Helsinki University and NASA.

SiC technology is of great interest for its possible use in power applications in space and accelerators. However, the current commercial technology is still very sensitive to particle radiation. The effects of heavy-ions on SiC power MOSFETs and diodes were previously studied through radiation tests, Molecular Dynamics (MD) and Technology Computer Aided Design (TCAD) simulations. The radiation test campaigns continued in 2019 and included also protons and neutrons. Moreover, in order to extend the exploration of the physics of failure, experiments were performed with heavy-ion microbeams. This allowed micron-accurate localization of the radiation-sensitive regions providing unique information for a deeper understanding of the SEE mechanisms in SiC technology.

Relevant papers:
The ion source group has long experience in ion source related research and development work. The present work can be divided into four separate domains: 1) development of ECR ion sources and positive and negative light ion sources, 2) development of ion beams in terms of beam variety, quality and intensity, 3) development of plasma and ion beam diagnostics and 4) fundamental plasma physics research. Computational physics plays a significant role in the aforementioned R&D work. As a result of the long-lasting and decisive high-quality work the JYFL ion source group has gained an active role in the international ion source community. The main partners of the JYFL team are: CERN, GANIL, GSI-FAIR, IAP-RAS, INFN-LNS, iThemba LABS, LBNL, LPSC, NSCL and UCLM. The JYFL ion source group is also coordinating networking activity, ENSAR2/MIDAS, in Horizon 2020 program. More information about the networking activities can be found from: http://www.ensarf7.eu/activities/networking-activities/midas and link therein.


HIGHLIGHTS IN 2019

Status of the new heavy ion source (HIISI): In the beginning of 2019 the first production run for the space electronics testing using the 16.2 MeV/u beam cocktail was successfully executed. As a result, the tests with 9.3 MeV/u ion beam cocktail were practically stopped and all production runs for the space electronics radiation testing were realized with HIISI. The intensity of Xe$^{44+}$ ion beam produced with HIISI clearly exceeds the intensity of Xe$^{35+}$ ion beam produced by the JYFL 14 GHz ECRIS. These charge states are required for 16.2 MeV/u and 9.3 MeV/u ion beam cocktails, respectively. Figure 1 shows a comparison between the JYFL 14 GHz ECRIS, SUSI and HIISI (2017/2019) in the case of highly charged xenon ion beams [1]. As the figure demonstrates, the performance of room temperature HIISI and fully superconducting SUSI is practically identical. The improved performance of HIISI from 2017 to 2019 is due to the installation of a stronger hexapole (from 1.3 T to 1.42 T), a new klystron with 17.4 GHz heating frequency making 3-frequency plasma heating (14.5 GHz + 17.4 GHz + 18 GHz) and the use of higher total microwave power possible (from 2.3 kW to 3.0 kW). The excellent performance of HIISI has encouraged us to begin developing a new 22 MeV/u heavy ion cocktail for irradiation tests of space electronics. Krypton will be the heaviest element in the cocktail and the required energy will be met with Kr$^{32+}$ ion beam. The first experiments with HIISI confirmed that the requested energy and fluence specifications can be met. The outstanding performance demonstrated by HIISI has made it an attractive option also for other facilities around the world. As an example, a project to construct a copy of HIISI for the GSI-FAIR facility has been started.

↑ Figure 1. Intensities of Xe ion beams produced by different ECR ion sources: JYFL 14 GHz ECRIS, SUSI at 18 GHz (4 kW) and HIISI in 2017 (14.5 GHz + 18 GHz/2.3 kW) and 2019 (14.5 GHz + 17.4 GHz + 18 GHz/3 kW). The xenon charge states of $35^+$ and $44^+$ required for the currently used 9.3 MeV/u and proposed 16.2 MeV/u beam cocktails are marked on the fitting curves.
**Plasma research:** Several important results in the ion source plasma research were achieved in 2019. Extremely fruitful collaboration with the IAP-RAS ion source team and their plasma theory group was successfully continued. A well-developed technique of measuring the Electron Energy Distribution (EED) of electrons escaping axially from the magnetically confined plasma of an ECRIS was used for the study of the EED in an unstable mode of plasma confinement, i.e., in the presence of kinetic instabilities. It was shown that nonlinear phenomena alter the EED noticeably [2]. A campaign to correlate the plasma bremsstrahlung with the EED of escaping electrons from stable and unstable ECRIS plasma was initiated to further improve the understanding of plasma instabilities.

A high-resolution monochromator (optical resolution 10 pm FWHM at 632 nm), developed at JYFL, has been used to determine for the first time non-invasively the ion temperatures of electron cyclotron resonance heated plasma [3]. The measured ion temperatures are almost an order of magnitude higher than conventionally agreed, challenging the currently prevailing understanding of ECR plasmas.

Several experiments have been performed to determine the real confinement time of ions in ECRIS plasma. The research work was realized by introducing small amount of secondary element into the plasma with sputtering and/or 1+ injection methods. Cumulative ion confinement times are probed by measuring decaying ion current transients in pulsed material injection mode. The work has been done in collaboration with the GANIL ion source group and the method has been applied in a charge breeder ECRIS and a conventional ECRIS yielding mutually corroborative results [4]. These results are especially relevant for rare ion beam (RIB) production, as the confinement time and the lifetime of stable isotopes can be used for estimating the extracted RIB production efficiency.

**Academy project:** The Academy of Finland granted a four-year funding for the project: “The effect of a magnetic field structure on the performance of an ECR source”. The first experimental campaign to study the effect of the magnetic field configuration on the plasma stability has been completed. During the project an innovative ECR ion source, which magnetic field structure differs significantly from the conventional one, will also be designed and realized. The magnetic design has been completed and the non-magnetized permanent magnets have arrived for the test assembly. The successful implementation of the prototype would open new opportunities for the further development of ECR ion sources, and various applications.

Relevant papers:


The research activities of the group can be divided into four main areas: i) fundamental studies of ion-matter interactions, ii) detector, data acquisition and analysis software development, iii) materials and especially thin film research and iv) application of ion beam techniques for materials studies. The key infrastructure of the group is the 1.7 MV Pelletron accelerator and all the research equipment in its beamlines. In Nanoscience Center (NSC) clean room the group is an active user of a helium ion microscope (HIM) and a versatile atomic layer deposition (ALD) tool. The group is an active link between the two research infrastructures, Accelerator Laboratory and Nanoscience Center.

www.jyu.fi/physics/accelerator/abasedmat
ION BEAM ANALYSIS AND HELIUM ION MICROSCOPE IN MATERIALS RESEARCH

The ion beam analysis tools (mainly TOF-ERDA, RBS and PIXE) have been extensively used in 2019 for the characterization of a large variety of samples. In 2019 started the development of a multi-detector (14 PIPS-detectors) setup for RBS. This setup with digitized data acquisition will be taken into use in early 2020. The analysis capabilities of the University of Jyväskylä’s helium ion microscope (HIM) have been greatly improved by installing a time-of-flight secondary ion mass spectrometer (TOF-SIMS) to the instrument located in the NanoScience Center cleanroom. With TOF-SIMS the HIM users have now access to elemental information with better than 10 nm resolution in addition to imaging with 0.5 nm resolution.

FIRST SPATIAL-ALD TOOL IN JYVÄSKYLÄ HAS BEEN TAKEN INTO USE

As part of the Jyväskylä ALD CoCampus (JYU and JAMK University of Applied Sciences collaboration) a spatial-ALD reactor Beneq TFS-200R has been taken into use at JYFL. This tool has the capability to do depositions on flexible substrates with size up to 300×120 mm². Currently there are capabilities to do Al2O3 and ZnO depositions and TiO2 is in preparation. The ALD CoCampus hosts in total two pulsed-ALD and two spatial-ALD tools.

H2020-funded RADIATE-project running 2019–2020

In 2019 the RADIATE (Research And Development with Ion Beams – Advancing Technology in Europe, https://www.ionbeamcenters.eu/) project started. The Accelerator Laboratory provides transnational access to ion beam analysis (TOF-ERDA and RBS) and helium ion microscopy. In joint research activities, our main responsibilities are with multidetector/multitechnique arrangements, high-resolution detectors and analysis software development.

Selected publications:
COSMOLOGY

Our group mainly works in the interphase between particle physics and cosmology. Our research topics include the dark matter and dark energy problems and baryogenesis problem, cosmic inflation and inhomogeneous cosmologies. Group currently consists of two permanent staff members, one postdoctoral researcher and five PhD-students.

www.jyu.fi/physics/particles/cosmology

QUANTUM TRANSPORT AND THE PHASE SPACE STRUCTURE OF THE WIGHTMANN FUNCTIONS

We study the phase space structure of exact quantum Wightman functions in temporally varying systems [1]. These functions display coherence shells around zero frequency, which carry the information of the local quantum coherence of particle-antiparticle pairs. We compute quantum currents created by a temporal change in a particle’s mass, comparing the exact Wightman function approach to other methods. We find that the semiclassical approximation works surprisingly well even for very sharp temporal features.

RENORMALIZATION GROUP IMPROVEMENT IN THE STOCHASTIC FORMALISM

We investigate compatibility between the stochastic infrared (IR) resummation of light test fields on inflationary spacetimes and renormalisation group running of the ultraviolet (UV) physics [2]. We show that the improved stochastic Langevin and Fokker-Planck equations which consistently include the renormalisation group effects in general differ from the standard stochastic equations with the renormalisation group improved potential. We illustrate the differences with the example of Yukawa theory during inflation.

ON THE VALIDITY OF PERTUBATIVE STUDIES OF ELECTROWEAK PHASE TRANSITION IN THE TWO HIGGS DOUBLET MODEL

We study nonperturbatively the electroweak phase transition in the Two Higgs Doublet model by using a dimensionally reduced effective theory at high temperature [3]. We discuss the shortcomings of the conventional perturbative approach based on the resummed effective potential. The infrared resummations and the convergence issues with large scalar couplings are better treated with perturbative methods within the effective theory. We find that in the presence of very large scalar couplings, strong phase transitions cannot be reliably studied with any of the methods.

NEUTRINO AND ASTROPARTICLE PHYSICS

Senior Researcher Władysław Trzaska

JYFL involvement in experimental neutrino and astroparticle physics dates back to 2006 when we took the scientific responsibility for the activities at the Centre of Underground Physics in Pyhäjärvi, including the cosmic ray project EMMA. At that time European neutrino community was making plans for a giant detector of a new generation. The subsequent LAGUNA and LAGUNA LBNO Design Studies chose the Pyhäjärvi mine as the preferred location both for the liquid scintillator detector (LENA) and for the liquid argon time projection chamber (GLACIER). However, obeying the ruling of the 2013 European Strategy for Particle Physics, the scientific and technological legacy of LAGUNA was transferred to the USA-based DUNE and the Chinese-based JUNO project.

With over 1132 collaborators from 188 institutions in 33 countries, DUNE (Deep Underground Neutrino Experiment) is the largest neutrino experiment in the world. One of the symbolic milestones of 2019 was the November 14th ground-breaking ceremony at Long-Baseline Neutrino Facility (LBNF) Near Site at Fermilab – the host of the accelerator complex to produce high-intensity neutrino beams and the location of the Near Detector. At the LBNF Far Site – the Sanford Underground Research Facility in Lead, South Dakota – preparations for the final excavation phase are nearing completion. The Ross shaft and the rock disposal tunnel are being refurbished. A 4200’ (1.3 km) conveyor is being installed to transport the estimated 800,000 tons of excavated rock from the shaft to the open pit. The Far Detector will be located in four elongated caverns with identically sized cryostats. The first two will house single-phase liquid argon detectors, the third will be for the dual-phase detector. The fourth, nicknamed “opportunity”, is intended for a future advance-design detector. Among the considered options are THEIA25 – a water-based liquid scintillator detector and ARIADNE – an optical readout dual-phase liquid argon TPC.

Substantial part of DUNE R&D is carried out at CERN. After the successful 2018 in-beam tests of ProtoDUNE single-phase detector, in 2019 the first cosmic tracks (inset) were observed with the dual-phase prototype (left).
With no possibility for a large liquid scintillator-based neutrino observatory in Europe, all the experts in the field have joined JUNO – the Jiangmen Underground Neutrino Observatory – a medium-baseline reactor neutrino experiment being constructed in Southern China. The main aim of JUNO is to determine the neutrino mass hierarchy and perform precision measurements of the Pontecorvo–Maki–Nakagawa–Sakata matrix elements. The project is very challenging but proceeding basically on schedule. Our team contributes primarily to the radiopurity measurements and to the cosmic-ray background studies for JUNO.

The prospects for the use of the infrastructure of the Pyhäsalmi mine for at least several years beyond the end of ore excavation have now been confirmed. In addition, Pumped Hydro Storage Sweden AB and Callio Pyhätäjärvi have signed a cooperation agreement to build a demo plant in the Pyhäsalmi mine. The purpose of the project is to design and develop a small-scale pilot plant that can later be utilized to implement a full-size power storage capacity of over 50MW. If realized, that would keep the mine open to science projects for several decades providing excellent infrastructure for high-energy cosmic-ray research and neutrino physics.

In 2019 no major funding was allocated for the research in the mine. To optimize the use of the available resources, the teams from JYFL, Kerttu Saalasti Institute, Sodankylä Geophysical Observatory, and NCBJ (National Centre for Nuclear Research in Lodz, Poland) have formed NEMESIS Collaboration. The main goal of NEMESIS (New Emma MEasurement with neutrons In cosmic Showers) is to register underground neutron bursts in coincidence with muon tracks. The experimental setup is based on the EMMA (Experiment with Multi-Muon Array) infrastructure, located at the depth of 75 m at the Pyhäsalmi mine in Finland. The average overburden of 210 m.w.e. corresponds to the cut-off energy of 50 GeV for vertical muons. The muons are registered with an array of high-granularity scintillator modules. Recently, the modules were successfully used to measure the total muon flux together with the angular distribution of the muon flux in the Canfranc Laboratory in Spain. The neutron detectors are provided by the team from NCBJ. The same team did neutron measurements in all major European underground laboratories.

Selected publications:
W.H. Trzaska et al. (2019), Acoustic detection of neutrinos in bedrock, EPJ Web of Conferences, 216. EDP Sciences, 04009, DOI: 10.1051/epjconf/201921604009.
M.G. Aartsen et al., Combined sensitivity to the neutrino mass ordering with JUNO, the IceCube Upgrade, and PINGU, (2020), Phys. Rev. D 101, 032006.
QCD THEORY

The QCD theory group studies different aspects of the strong interaction at high energy and density. In addition to the phenomenology of high energy nuclear collisions at the LHC and RHIC, we are involved with physics studies for planned colliders such as the EIC and FCC. We use weak coupling QCD renormalization group equations to understand the partonic structure of hadrons and nuclei. Our specialties also include using this information to understand the formation of a thermalized quark-gluon plasma and modeling its subsequent evolution with relativistic hydrodynamics. In 2019, Pablo Guerrero Rodríguez started as a new postdoc, Kirill Boguslavski moved to TU Wien, Mark Mace to the private sector, and Vadim Guzey returned to the Petersburg Nuclear Physics Institute. Petja Paakkinen defended his PhD thesis and moved to a postdoc position in Santiago de Compostela.

www.jyu.fi/physics/particles/urhic

IMAGING THE NUCLEUS WITH HIGH-ENERGY PHOTONS

Understanding how quarks and gluons are distributed inside nucleons and nuclei is a central problem for the theory of strong interactions. The distribution of gluons in transverse coordinate space in a high energy nucleon or nucleus has been a focus of recent attention in the community. For example, this transverse geometry is crucial for understanding the spatial structure of the quark gluon plasma created in ultrarelativistic heavy ion collisions. Experiments have also started to explore the transverse momentum distribution of partons in nuclei. In a recent review article [1] we explored recent progress in measurements of the spatial distribution of gluons, both in ultraperipheral collisions of heavy nuclei at the LHC and in a future electron–ion collider with high luminosity and collision energy. These processes can be used to probe both the average of and fluctuations in how quarks and gluons are distributed spatially inside the proton, and in heavy nuclei.

HIGHLY OCCUPIED GAUGE THEORIES IN 2+1 DIMENSIONS: SELF-SIMILAR ATTRACTOR

The color field configurations in the initial pre-equilibrium stages of heavy ion collisions are approximately boost invariant, and thus effectively two dimensional. We studied [2] the long-time behavior of a two-dimensional nonabelian gauge field using classical-statistical simulations. We discovered that irrespective of the details of the initial condition, the far-from-equilibrium evolution of these highly occupied systems approaches a unique universal attractor at high momenta. We then extracted the scaling exponents and the form of the distribution function close to this nonthermal fixed point, finding that the dynamics are governed by an energy cascade to higher momenta with analytically calculable scaling exponents. The values of these exponents can be obtained exactly from parametric estimates within kinetic theory. However, in two spatial dimensions (unlike three) the scale hierarchy between hard particle-like and soft field-like degrees of freedom underlying the kinetic theory description completely breaks down. Thus, despite explaining the scaling exponents, a kinetic theory cannot qualitatively describe the particle distribution in the system. We also observed, in the scalar sector of the theory, an enhancement of the field correlation function at small momenta above the thermal or perturbative estimate, reminiscent of a condensation-type behavior.
IMPACT OF CMS PROTON-LEAD DIJET MEASUREMENTS ON NUCLEAR PDFs

Our EPPS16 nuclear parton distribution functions (PDFs), the first set of nuclear PDFs constrained by LHC data, are now a new standard in the field. In spite of their success, these PDFs are still poorly determined especially in the gluon sector. High-precision dijet measurements by CMS at the LHC in proton-lead (pPb) and proton-proton (pp) collisions at 5.02 TeV, however, offer now important new constraints for the gluons. The impact of a new data set on PDFs with Hessian error sets can be estimated – without re-doing a full global PDF fit – by applying the Hessian reweighting method developed earlier in our group. In [3], we improved this approach formally further and applied the improved analysis to the EPPS16 PDFs by using the CMS data on the pPb-to-pp nuclear modification ratio of the normalized dijet spectra. We observed (see Fig. 1) a dramatic reduction of the gluon PDF uncertainties in the mid-x antishadowing region, and that the reweighted result supports slightly more suppressed small-x gluons than in EPPS16. In addition, our reweighting study with the pp data provided interesting new information about the gluons in the free proton as well.

DOUBLE D-MESON PRODUCTION IN PROTON-PROTON AND PROTON-LEAD COLLISIONS AT THE LHC

Inclusive LHC measurements of hadrons with a heavy charm quark provide important tests for calculable QCD dynamics in proton-proton and proton-nucleus collisions. Applying next-to-leading-order perturbation theory, modern PDFs and fragmentation functions, and our recently developed heavy-quark mass scheme, we compute inclusive production of two D mesons, or D and Λ_c, by accounting for contributions

† Fig. 1. The EPPS16 nuclear modification of the gluon PDF in a lead nucleus vs. the momentum fraction $x$ at a scale $Q^2 = 10 \text{ GeV}^2$, before (light blue) and after (dark blue) the reweighting. Figure from [3].
from single-parton scatterings (SPS) and double-parton scatterings (DPS) [4]. For the hadron pairs of opposite-sign charm, SPS dominates over DPS but for the like-sign charm pairs DPS becomes dominant (Fig. 2). With the well-working framework, and our EPPS16 nuclear PDFs, we finally predict the double D-meson production cross sections in proton-lead collisions (Fig. 2) to be measurable at the LHCb kinematics with the Run-II data and estimated selection efficiencies. Thanks to the strongly enhanced DPS contributions here, this observable should provide direct evidence of hard double-parton scattering with a nuclear target.

**RESISTIVE DISSIPATIVE MAGNETOHYDRODYNAMICS FROM THE BOLTZMANN-VLASOV EQUATION**

The space-time evolution of strongly interacting systems of quark-gluon plasma and hadron gas created in ultrarelativistic heavy-ion collisions is describable with relativistic dissipative hydrodynamics. Second-order theories play nowadays a key role in understanding the dynamics of nucleus-nucleus collisions at the LHC, and in interpreting bulk observables like transverse-momentum asymmetries there. The presence of strong electromagnetic fields in non-central collisions calls for a self-consistent magnetohydrodynamic framework. Building on our previous formal developments, we derived in [5] the equations of motion for resistive 2nd-order dissipative magnetohydrodynamics from the Boltzmann-Vlasov equation, assuming a system of charged spin-0 particles with elastic collisions and using the 14-moment approximation. The novel feature is the finite resistivity leading to new terms proportional to the electric field in the equations of motion. The Navier-Stokes limit of the charge-diffusion current is shown to correspond to the Ohm’s law, and the electric conductivity to be related to the thermal conductivity.

ALICE EXPERIMENT
AT THE CERN LHC

Senior Lecturer Sami Räsänen and
Senior Researcher Władysław Trzaska

A Large Ion Collider Experiment – ALICE – is the dedicated heavy ion measurement at the CERN LHC, designed to study the properties of the Quark Gluon Plasma (QGP). QGP is one of the exotic states of the matter, that prevailed a few microseconds after the Big Bang, when the temperature of the Universe was about 2000 billion degrees.

ALICE has excellent particle identification and low momentum tracking capabilities that allow, for example, heavy flavour measurements down to very low momenta. One example of the performance of ALICE detector is the 2019 measurement for the lifetime of the hypertriton [1], the most precise result in the world so far.

ALICE collaboration has over 1900 members coming from 175 institutes in 39 countries.


CERN accelerators are currently undergoing a major performance upgrade. To cope with the increased luminosity and collision rate during the upcoming LHC Run 3 and 4, ALICE is replacing and modernising its infrastructure. During the March 2019 Fest Colloquium ALICE celebrated the achievements of the retiring subsystems, including the timing detector T0, which was largely assembled and tested in Jyväskylä. The success of the T0 project lead the way to the design and approval of the new Fast Interaction Trigger (FIT) detector. Starting from the LHC Run 3, FIT will provide the fast trigger, luminosity, centrality, and event plane measurements for heavy ion collisions.

The original FIT design consisted a new fast timing array FT0 and a large scintillation ring FV0. In 2019, the functionality of FIT was enlarged by the addition of the Forward Diffractive Detector (FDD), the successor of the ALICE AD detector from Run2. In recognition of the importance of the detector for the operation of ALICE, FIT Project Leader (W.H. Trzaska) became a permanent ex-officio member of the Management Board representing all Forward detectors.

Cross section of the FV0 detector at FIT lab in CERN.
Photo by W.H. Trzaska. ↓
During 2019 FIT detector entered the final production phase and several milestones were reached. For example, the C-side of the FTO detector was fully completed and integrated with new Muon Forward Tracker, that also is part of the ALICE upgrade. Our group took additional responsibilities for System Run Coordination and Analysis Framework (M. Slupecki), and also for Detector Control System (H. Rytkönen).

In the physics data analysis, our group remained focused on jet analysis and collective flow including measurement of the higher order harmonics, where a hint of a deviation from the trend set by viscous damping was seen. In some models, this is related to acoustic peak.

In June 2019 T. Snellman defended his PhD-thesis [3] on jet fragmentation transverse momentum measurements in proton-proton and proton-lead collisions. The results were found to be similar for both systems giving stringent constraints to models expecting significant broadening of jets in cold nuclear matter. O. Saarimäki studied the di-jet mass distributions in proton-proton and proton-lead collisions. Like in many studies by the LHC experiments, also the di-jet mass does not show significant difference in small collisions systems, at least in the minimum bias data sample. The main goal of Oskari’s analysis is to measure the centrality dependence of the di-jet mass in lead-lead collisions. The production vertices of the di-jets may lie, on the average, closer to the center of the fireball while in the case of single jets the distribution of vertices is expected to be biased close to surface. Hence the measurement could provide new constraints to the jet energy loss in the strongly interacting matter.

Our conference highlights include a plenary talk on new detectors at VCI 2019 (W.H. Trzaska) as well as one talk on flow harmonics (J. Parkkila) and two posters (O. Saarimäki, DJ Kim) at Quark Matter 2019.

We also contributed significantly to the analysis of anisotropic flow in various collision systems [2].

↑ High-order flow harmonics measured by ALICE. Observing $v_9 > v_8$ may indicate presence of an acoustic peak.

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In 2019 Physics Department started a new kind of societal commercial activity: Radiation Protection Expert (RPE) service. By definition the service is expert consultation without a direct link to research, except through the Accelerator Laboratory scientists involved in the activity. The new radiation legislation requires that all users of ionizing radiation need to use external RPE advice and consultation if the local radiation protection officer (RPO) does not have this qualification. More than 10 % of the RPEs licensed to work in the industry in Finland are employed in Accelerator Laboratory, so it is not a surprise that the number of signed contracts with companies was significant already in 2019.

The Industrial Applications group of the Accelerator Laboratory continued the utilization of RADEF facility under ESA’s Technical Research Programme (TRP). The contract was again renewed in 2018 and will continue for three years with an option of two more years. In the contract, we are obliged to offer K-130 cyclotron beam time for ESA and European space industry. In addition, we provide irradiation tests with our LINAC electron accelerator. The use of RADEF’s commercial beam time in 2019 was 1299 hours corresponding to about 20 % of the total running hours of the K-130 cyclotron. In total, 49 test campaigns for 30 companies were performed at RADEF. The commercial revenue in 2019 was over 1 M€. In addition, Horizon 2020 Marie-Curie (MSCA) RADSAGA training network provides an intersectoral structure based on a unique mixture of private companies. The host companies for the future secondment periods of our three RADSAGA graduate students include 3D-Plus (FR), Airbus D&S (FR), MAGICS Instruments (BE), Yogitech (part of Intel’s IoT Group) and Zodiac Aerospace (FR).

The Accelerator Based Materials Physics group within the Accelerator Laboratory has continued its active industrial collaboration in the forms of characterization of thin films and small thin film related projects both with international and domestic companies. A new spatial atomic layer deposition (ALD) reactor for small scale piloting has been taken into use and, in collaboration with JAMK University of Applied Sciences, the thin film activities marketed under ALD CoCampus umbrella have interested many companies. An EU funded access project RADIATE (https://www.ionbeamcenters.eu/) started in 2019 and provides access also for companies benefitting from ion beam analysis and helium ion microscopy.

The Thermal nanophysics group has well established collaboration with a few companies in Finland and abroad. The superconducting radiation detector work has involved collaboration with global, industry leading small and medium scale high tech companies, including one from the USA. In addition, national laboratories such as VTT Micronova, NIST Boulder, NASA Goddard Space Flight Center and Space Research Organization Netherlands (SRON) have been involved. Contacts to the Jyväskylä start-up company Recenart are also close. In 2019, collaboration with globally leading nanofabrication tool companies continued, in particular with Raith GmbH.
During the year 2019, the primary research activity the Complex materials group was related to safety analysis of repositories of spent nuclear fuel. In particular, X-ray tomographic techniques were developed and used in studies of the hydromechanical behavior of bentonite clay, which is planned to be used as mechanical buffer and release hindrance material protecting the used fuel canisters in the deep underground deposition sites. The techniques used allow detailed ‘4D’ measurement of water transport and the resulting swelling deformation of the clay material. The results will be used in developing and validating numerical models used in long-time safety analysis. This work was carried out in the framework of KYT2022 Research Programme funded by the Ministry of Economic Affairs and Employment of Finland, and in two European consortium projects Beacon and EURAD, funded by EU/Horizon 2020 Framework Programme. The main industrial partner in this research is Posiva.

In addition, the industrial collaboration included several Finnish companies and applied research institutes such as VTT Technical Research Centre of Finland and The Geological Survey of Finland, GTK.

At the Nanoscience center, department’s personnel was participating in the organization of Business Day. Attracting 16 companies and about 110 participants, the event was aimed to bring companies and students together, to tell companies about our research and provide students opportunities for networking. The event was successful to such an extent that it will likely be made an annual event.
ONLINE MATERIAL FOR ON-DEMAND MATH SUPPORT FOR STUDENTS

In 2019 we launched an effort to alleviate students’ challenges in mathematics during problem-solving by compiling online material, “matikkapakki” (math toolbox). The idea was to "lubricate students' mathematical machineries" by providing short, pedagogical presentations of topics in mathematics that are known to be challenging. The lubricative aspect was enhanced by presenting the mathematics using common physics notations so that skills acquired from mathematics courses can be more easily transferred to physics contexts. The material was devised within a teaching development project that involved several people from the departments of physics, chemistry, and mathematics; the actual material was produced by two effective mathematics students. The online material, which is still developing and expanding, resides in the address https://tim.jyu.fi/view/kurssit/matematiikka/matikkapakki/etusivu.

TRAINING YOUNG PHYSICS MINDS

As in many years before, we continued organizing training for advanced upper secondary school students and managed Finnish participation in international physics competitions. We arranged two experimental physics training camps at the department: one for students who succeeded in national physics competition and one for the Finnish and Estonian teams representing their countries in the International Physics Olympiad, organized this year in Israel. Topi Löytäinen, Miha Marttinen, and Heikki Mäntysaari from the Physics department participated in these training activities, collaborating with the Department of Teacher Education and upper secondary school teachers. The Finnish team succeeded well in the Olympiad, with Finland being one of the only three European countries whose students were awarded a gold medal.

AT THE FOREFRONT OF TEACHING DEVELOPMENT

At the end of 2019, department’s work on teaching development was recognized by university’s teaching development prize. The prize was related to the development of the Primetime learning approach, which is currently being adopted at the universities of Eastern Finland, Tampere, Oulu, and Helsinki and which has attracted also plenty of international interest.

EDUCATION

Senior Lecturers
Pekka Koskinen and Juha Merikoski,
Postdoctoral Researcher Heikki Mäntysaari,
University Teacher Jussi Maunuksela

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