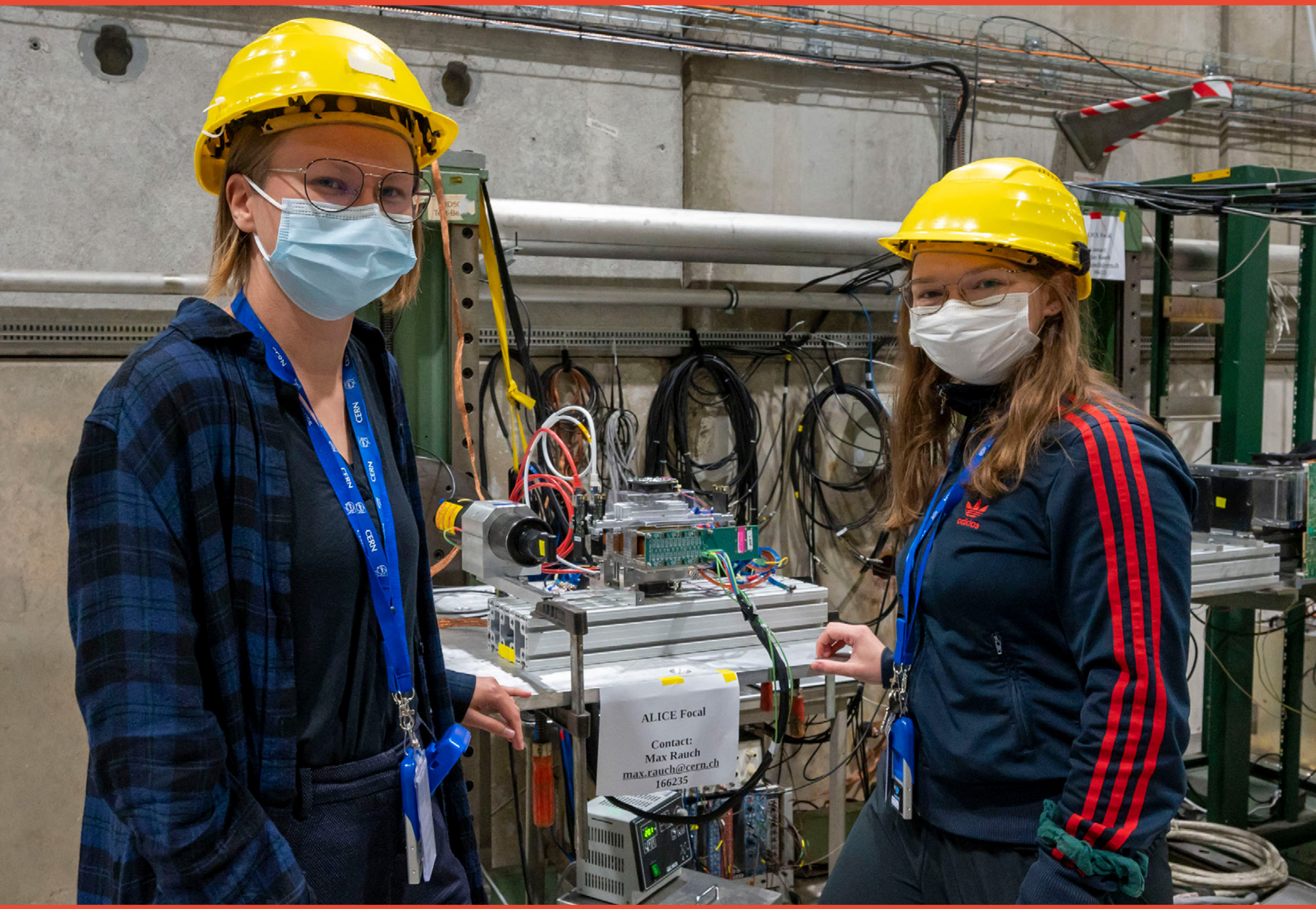

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

ANNUAL REPORT 2021
DEPARTMENT OF PHYSICS

For JYU. Since 1863.

DEPARTMENT OF PHYSICS

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 in the Nanoscience Center, located next to the Department and housing a part of our personnel. Our Department is highly international and we collaborate with numerous universities and research institutes abroad, such as CERN.

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

STATISTICAL DATA FROM 2021

175
PERSONNEL

Professors incl. associate professors **20**
Senior lecturers and researchers **24**
Postdoctoral researchers **40**
Doctoral students **50**
Technical staff **26**
ERC grantees **3**
+ Research assistants (MSc students) **15**

• Personnel counted in person-years

~310
UNDERGRADUATE STUDENTS
of which new students **59**
Doctoral students **~70**

22 BSC DEGREES
22 MSC DEGREES
0 PHLIC DEGREES
8 PHD DEGREES

Median time to complete MSc (years) **6**

144 NUMBER OF FOREIGN VISITORS
201 IN VISITS
30 VISITS ABROAD

~235 Peer reviewed publications
~220 A1-A3 articles
~15 A4 Conference proceedings
~10 Other publications

CONFERENCE AND WORKSHOP CONTRIBUTIONS
Invited talks **90** | Other talks **~140** | Posters **~30**

14.8
FUNDING (million €)

- Basic financing **8.3**
- Sales (contract research) **1.4**
- Income according to separate laws (mainly EU funding) **2.2**
- Government grants **2.8**
- Other income **0.2**

CONTENTS

Editors:
Kari J. Eskola, Tuomas Lappi

Cover picture
Wladyslaw Trzaska

2021

ANNUAL REPORT
Department of Physics

Preface

This Annual Report provides an extensive summary of the activities at the Department of Physics during the year 2021.

The main research fields at the Department of Physics are materials physics, particle physics and nuclear physics. All these fields include both theoretical and experimental research groups. A majority of the materials physics research is concentrated in the interdisciplinary Nanoscience Center. Most of the experimental nuclear physics is carried out in the Accelerator Laboratory, which is one of the leading European user facilities in its field. In addition to broad experimental and theoretical activities within the department, the department also works, in coordination with the Helsinki Institute of Physics, in close connection to large international infrastructures such as CERN and FAIR.

The Covid-19 pandemic started in mid-March in 2019 and still continued the full year 2020. Most of the teaching was done remotely all the time, and the teaching staff was also mostly working remotely the whole year. During the year there were times with higher numbers of infections as well as better times, but the restrictions were in place all the time. Our department managed the situation quite well: the number of infections remained at a very low level until the vaccinations started, and the whole year we were able to keep the laboratories open and even have some visitors, who were willing to follow the strict policies of testing and several days of quarantine before entering the department. The Covid-19 time clearly taught us many new skills, and we are now much better prepared if something similar happens again.

Despite the pandemic and lack of travel, the research remained at a high level at the department. The most significant development in 2021 was the positive decision by the Academy of Finland to fund the Centre of Excellence in Quark Matter for eight years starting from 2022. This single-sited CoE, led by professor Tuomas Lappi, is a recognition of the quality of both theoretical and experimental research done at the department. Research was renewed by several new recruitments. These included the recruitment of Shawulienu Kezilebieke to an assistant professorship (tenure track) and Dong Jo Kim to a senior lecturer position in experimental particle physics. Sami Malola and Tuomas Puurtinen were selected to staff scientist positions in computational nanoscience. At the end of the year associate professor Anu Kankainen was promoted to full professor starting from 1.1.2022. In the autumn Shawulienu Kezilebieke received ERC starting grant funding for five years, and now there will be two scanning tunneling microscopes for different projects at the Nanoscience Center. The retirement of our former head, professor Markku Kataja at the end of the year 2021 was a big loss for the department. Although he continues to work as an emeritus, the daily discussions with him during coffee breaks and his humane leadership are missed by many of us.

In 2021 the Ylistö renovation project did not proceed as originally planned. Still in summer 2021 the plan was to start the renovation in January 2022 from the Department of Physics building and then gradually renovate all the Ylistö buildings together with some extensions. The original schedule was postponed towards later in summer 2021 and now in spring 2022 it is unclear what will eventually take place and when. There has been room for improvement in this process. Another thing that can be improved are our graduation records. The number of BSc, MSc and PhD graduations at the physics department are not at the level they should be. New development steps have been initiated and most probably the numbers will rise in the future although changes are slow. The year 2021 will also be remembered by many because of the gas explosion accident which took place at the Accelerator Laboratory. One person was unfortunately seriously injured in this event but luckily later recovered well. The cause of the accident is well understood and it has already led to further improvements in our training, instructions and safety culture.

The Department of Physics is in good shape and in a good position and ready for interesting new developments in the coming years. Financially the situation is good, as the final result has been slightly positive for many years now. There is continuous renewal of the staff and research, which keeps the department in pace and even ahead of the rest of the world. The influence of societal impact is expected to grow in coming years. The Department has taken the initiative towards this direction in 2021 by starting a process to recruit a professor-in-practice. With our dedicated staff and hard-working students the future of physics will be bright in Jyväskylä and in Finland.

Timo Sajavaara
HEAD OF DEPARTMENT

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JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

New Center of Excellence in Quark Matter

↑ From the left Dong Jo Kim, Tuomas Lappi, Sami Räsänen, Kari J. Eskola, Hannu Paukkunen

Tuomas Lappi
COE DIRECTOR

At the end of 2021, after an open call covering all areas of research, the Academy of Finland chose 11 new Centers of Excellence (CoE) for the period 2022–2029, out of 184 applications on the first and 34 on the second round. The University of Jyväskylä participates in 4 of the 11 new CoE's. The CoE in Quark Matter, formed by the QCD theory and ALICE experimental groups, is fully within the Department of Physics. This is the first time that the CoE program of the Academy of Finland has a CoE in particle physics, and with such a strong focus on research at CERN.

The research topics in the CoE revolve around different aspects of the interactions between quarks and gluons, the elementary constituents of ordinary matter. While Quantum Chromodynamics (QCD), the fundamental theory of the strong interaction, is known, it is challenging to connect it to experimental observations. The research in the CoE covers all the different aspects needed to make this connection, from detector design and data analysis to simulations, global fitting, models and basic theory. The presence of these different methodological aspects in the same unit is one of our major strengths. A particular research focus is to understand how, in a relativistic heavy ion collision, matter turns into a deconfined strongly interacting quark-gluon plasma, and to understand the properties of this form of matter by a combination of theoretical and experimental research.

The CoE in Quark Matter consists of five research teams, three theoretical and two experimental ones. The team of the CoE director Tuomas Lappi and Heikki Mäntysaari studies QCD scattering in the nonlinear high energy limit. The team of Kari J. Eskola (CoE vice-director) and Harri Niemi focuses on extracting the properties of the quark gluon plasma by modeling its spacetime evolution in heavy ion collisions. The team of Hannu Paukkunen and Ilkka Helenius applies perturbative QCD and Monte Carlo simulations to collider phenomenology. The theoretical research is related both to experiments at the CERN Large Hadron Collider, and to ones that will be carried out in the future Electron-Ion Collider (EIC) in the US. The CoE experimental groups are members in the ALICE collaboration, which operates one of the major detectors at the LHC. The team of Dong Jo Kim concentrates on multiparticle correlation ("flow") analysis in ALICE. The team of Sami Räsänen focuses on jets and electromagnetic probes, as well as participation in future detector upgrades. Both the theoretical and experimental teams are also a part of the Helsinki Institute of Physics, a national institute which coordinates Finnish participation in international accelerator laboratories, in particular CERN.

THE YEAR 2021 AT THE NSC

Tero Heikkilä

A Finnish comedian André Wickström tweeted a few days ago that he felt he should have taken more out of the year 2019. I cannot help but agree with him. Nevertheless, life goes on and even in these dire times there are many reasons to be happy. One of them is the great new scientific director of the Nanoscience Center, Lotta-Riina Sundberg, who started in the position in the beginning of the year 2022. For me the four years as the NSC director were interesting, intense and educative. Eventually for me it was a bit of a variation of the Peter's principle, reaching the state of poor creativity.

One big event for the NSC during 2021 was the International Advisory Board (IAB) meeting that took place in April. Because of the pandemic it was organized as an online event, which was far from an optimal situation as perhaps the most important discussions during usual IAB meetings are held outside the official agenda. The IAB's report focused on praising the sense of drive and enthusiasm and the inclusive environment with a healthy leadership climate and a flat hierarchy. Identifying weaknesses is harder in an online event. However, the main threat the IAB identified was that of too many isolated small groups not collaborating with each other.

Starting from the end of 2020 and during 2021, the NSC renewed its research profile by creating five new research groups related to positive funding decisions and new strategic initiatives. We also made several infrastructure investment decisions especially related to various imaging tools. One of the new groups is in physics, as we were able to recruit Assistant Professor Shawulienu, who will build a low-temperature scanning tunnelling microscope laboratory that will finally allow for atomic resolution imaging within the NSC. Shawulienu got ample support for his work as he first got the Academy research fellowship, and later the ERC starting grant. You can learn more about Shawulienu and other NSC highlights from the NSC 2021 newsletter, at the NSC website.

Increasing the number of research groups inside the NSC allows leveraging the use of our infrastructure and application areas of our research. At the same time there is risk of fragmentation of research without reaching the infamous critical mass in any topic. I believe this risk can be mitigated by frequent discussions between NSC groups and financial support for collaboration such as our postdoc projects. This is where the inclusive environment is a great asset. However, it does not stay without constant nourishing, and frequent face-to-face meetings. Because of the pandemic we have had to postpone our center-wide meetings, but hopefully we will be able to organize them soon.

I wish Lotta-Riina success as the new NSC director and look forward to seeing the constant improvement of the NSC as a site of high-level research, both experimental and theoretical.

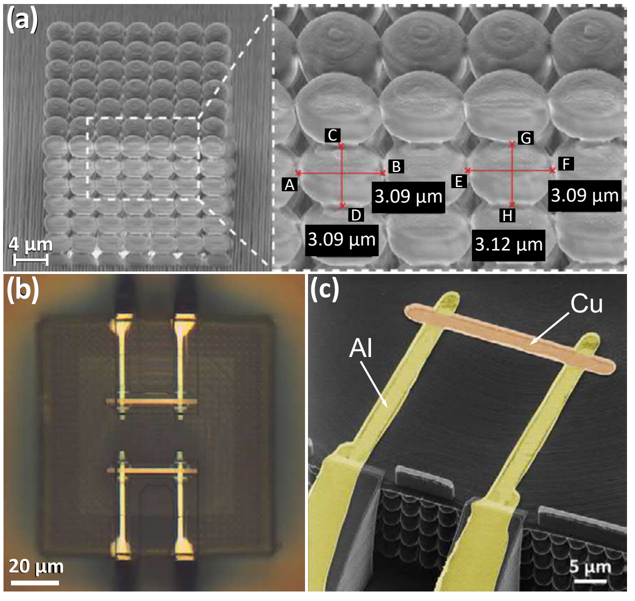
THERMAL NANOPHYSICS AND SUPERCONDUCTING DEVICES

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 effects
- 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 microscopy (HIM) and 3D laser lithography

https://www.jyu.fi/science/en/physics/research/materials-physics/thermal-nanophysics



↑ Figure 1. (a) A scanning electron micrograph of a three-dimensional phononic crystal (PnC) of touching spheres of period ~3 µm. (b) An optical micrograph of the finished structure viewed from the top, including the heater and thermometer devices for measurement. (c) A false color helium ion micrograph of a PnC structure with heater and thermometer on top (yellow =Al and orange = Cu).

NANOSCALE THERMAL TRANSPORT

We continue to have a strong focus on the theory and experiments of nanoscale thermal transport. In 2021, the highlight of the activity were the first measurements and simulations of thermal conduction in nanoscale three-dimensional phononic crystals, fabricated using direct write 3D laser lithography [Heiskanen2021]. Experiments performed at sub-Kelvin temperatures showed a surprising large enhancement of thermal conductance, up to an order of magnitude over a bulk structure made from the same polymeric material. This effect was not reproduced by our finite-element method simulations based on coherent modification of the phonon dispersions due to the 3D phononic structure, which predicted a strong reduction of thermal conductance. Thus, it is safe to say that we do not currently understand the observed enhancement, and further work is required on this topic.

DEVELOPMENT OF SUPERCONDUCTING DEVICES AND MATERIALS

The group's activities on developing novel superconducting devices have continued in 2021. In addition to ongoing work in the SUPERTED EU FET open project to demonstrate the world's first superconductor-ferromagnet X-ray detector, we have continued our work on using pulsed laser deposition (PLD) as the basis for ultrahigh-quality advanced superconductor materials. In 2021 we succeeded in fabricating normal metal - insulator - superconductor (NIS) tunnel junctions using superconducting titanium nitride (TiN) grown by PLD [Torgovkin2021]. PLD grown TiN is a promising material for superconducting applications, as its critical temperature can be tuned to be above the liquid helium boiling point (4.2 K), and it has been shown to have low losses in the microwave frequencies, which is relevant for quantum information science and ultrasensitive detector research, for example. We also demonstrated two different techniques for the formation of the tunnel barrier, using a thin aluminum oxide layer, or the direct oxidation of the TiN surface.

NOVEL NANOFABRICATION AND IMAGING TECHNIQUES FOR INTERDISCIPLINARY PROJECTS

The interdisciplinary collaborations using novel nanofabrication techniques such as 3D lithography and helium ion microscopy (HIM) and modification of materials have continued in 2021. In addition to the publication of the very first review article on the biological applications of helium ion microscopy [Schmidt2021] in collaboration with scientists from the Helmholtz-Centre for Environmental Research in Leipzig, Germany and the University of Bristol, UK, we helped microbiologists from the Danish company Novozymes with HIM imaging to study bacterial cell-wall polymer (peptidoglycan) breakdown [Fredriksen2021].

Selected publications

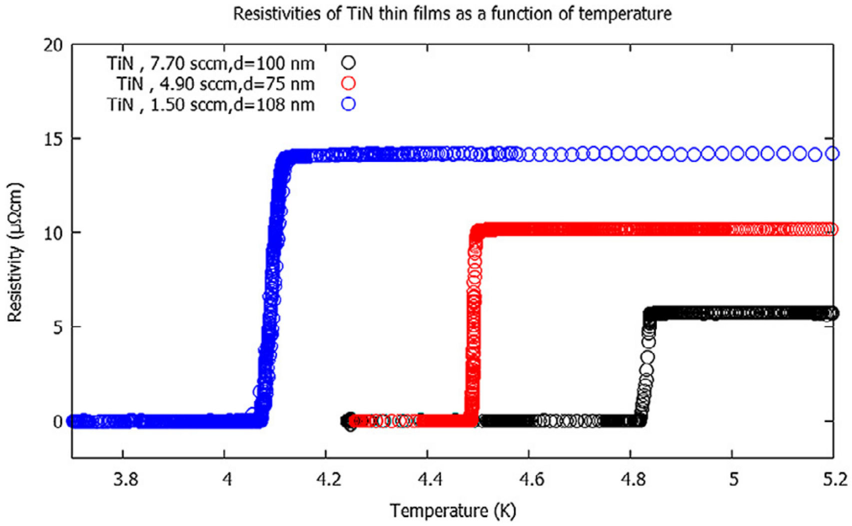
[Heiskanen2021] S. Heiskanen, T. A. Puurtinen, and I. J. Maasilta, *Controlling thermal conductance using three-dimensional phononic crystals*, APL Materials 9, 081108 (2021)

[Torgovkin2021] A. Torgovkin, A. Ruhtinas, and I. J. Maasilta, *Normal Metal-Insulator-Superconductor Tunnel Junctions With Pulsed Laser Deposited Titanium Nitride as Superconductor*, IEEE Trans. Appl. Supercond. 31, 1100604 (2021)

[Schmidt2021] M. Schmidt, J. M. Byrne, and I. J. Maasilta, *Bio-imaging with the helium-ion microscope: A review*, The Beilstein Journal of Nanotechnology 12, 1 (2021)

[Fredriksen2021] C. Østergaard Frederiksen, M. Thorup Cohn, L. Kobberøe Skov, E. G.Wedebye Schmidt, K. M. Schnorr, S. Buskov, M. Leppänen; I. Maasilta; E. Perez-Calvo, R. Lopez-Ulibarri, and M. Klausen, *A muramidase from Acremonium alcalophilum hydrolyse peptidoglycan found in the gastrointestinal tract of broiler chickens*, J. Ind. Microbiol. Biotechnol. 48, kuab008 (2021)

↓ Figure 2. Resistivity as a function of temperature of PLD grown TiN thin films deposited using different N_2 flow rates.



MOLECULAR TECHNOLOGY

Professor Markus Ahlskog

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.

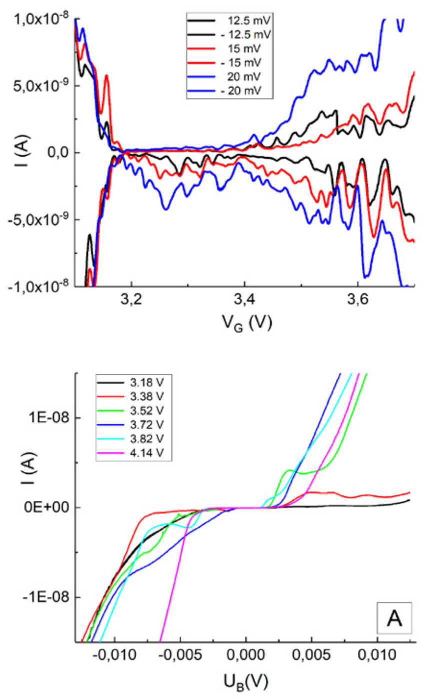
https://www.jyu.fi/science/en/physics/research/materials-physics/molecular-technology

TRANSPORT IN MWNTS

Arc-discharge synthesized multiwalled carbon nanotubes (MWNT) exhibit a good quality compared to the more common type of MWNTs synthesized by CVD methods. Common to nearly all experimental work on the electronic transport behavior of the high quality MWNT is the view that the low bias conduction occurs solely in the outer layer, which is well founded if the outer layer is of metallic character. The transport gap in semiconducting MWNTs has a more complex behavior than the corresponding one in semiconducting single wall carbon nanotubes (Fig. 1(a)). In particular, we observe regularly negative differential resistance within this transport gap (Fig. 1(b)). In the typical case these properties can be explained as due to the involvement of the next inner layer in the conduction at modest bias voltages. We present a rough model for the transport characteristics that builds on a tunnelling resistance between the outer and second layer of the MWNT [1].

OTHER MEASUREMENTS ON MWNTS

With MWNTs structural characterization is most pertinent. In a collaborative work [2], we reported Raman spectroscopy, Scanning probe microscopy, conductivity measurements, and Force microscopy on single arc-discharge MWNTs. The results demonstrate their high quality. This collaboration has continued especially within the topic of Resonant Raman spectroscopic measurement of single MWNTs. Such measurements can produce varying information and are relatively easy to integrate with transport measurements of single MWNTs.



↑ Figure 1. a) The core region of the transport gap in a semiconducting MWNT of diameter 8 nm measured at positive and negative bias voltage. b) IV-curves measured at the gate voltages indicated in the Label box. Asymmetry and negative differential resistance are seen in both graphs.

Selected publications

[1] M. Ahlskog, O. Herranen, J. Leppäniemi, D. Mtsuko, *Electronic Transport in Semiconductive Multiwalled Carbon Nanotubes*, Under review.

[2] Markus Ahlskog, Matti J. Hokkanen, Dmitry Levshov, Krister Svensson, Alexander Volodin, Chris van Haesendonck, *Individual arc-discharge synthesized multiwalled carbon nanotubes probed with multiple measurement techniques* Journal of Vacuum Science and Technology B, 38, 042804 (2020).

MOLECULAR ELECTRONICS AND PLASMONICS

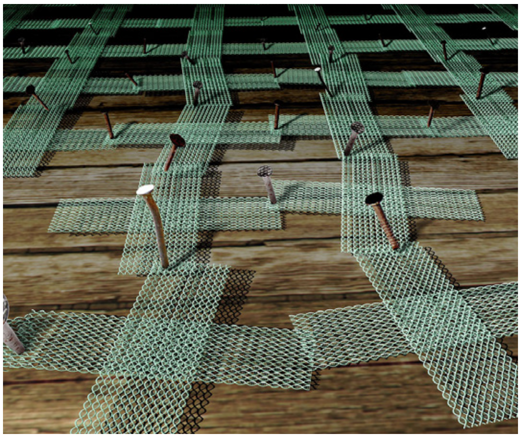
Associate Professor Jussi Toppari

We study nanoscale electronics, plasmonics, and photonics – concentrating on phenomena involving molecules as active components or as building blocks. The main fields are:

- Utilization of self-assembled DNA structures, like DNA origami, and their modifications in nanofabrication of electrical and optical/plasmonic nanodevices.
- Strong light-matter coupling. Strong interaction of photoactive molecules with confined light, like surface plasmons and cavity photons, creates new hybrid light–matter states, i.e., polaritons, which provide promising paradigm for controlling photochemical reactions. This new field is called *polariton chemistry*.

We also had new results within our collaboration on thin film Si solar cell development [1].

https://www.jyu.fi/science/en/physics/research/materials-physics/molecular-electronics-and-plasmonics

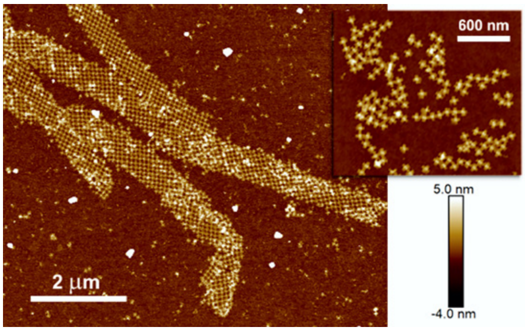


↑ Figure 1. Artistic view of fabrication of a 2D-lattice out of nanoscale DNA origami.

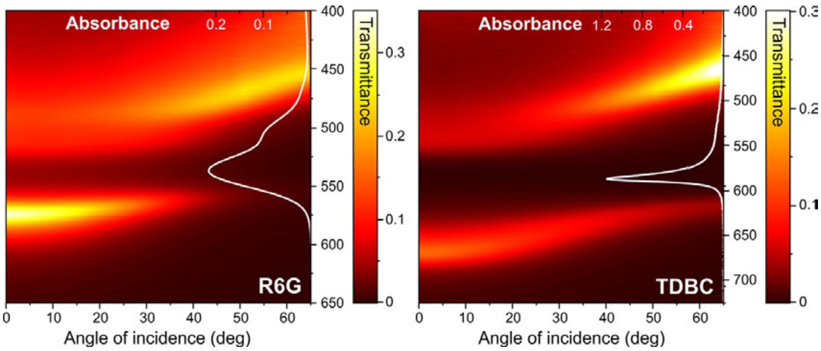
TOWARDS METAMATERIALS BY DNA SELF-ASSEMBLY

We have extended our earlier DNA-assisted-lithography (DALI) to utilize also other bio-templates, and to support any possible substrates [2]. In addition, we are developing a DNA self–assembly –based method to fabricate metallic nanostructured metasurfaces. This would usually demand very precise lithography, such as e-beam lithography, which takes an enormous amount of time to cover the needed large surfaces. Our goal is to combine DALI with the hierarchical self-assembly of DNA origami on the solid substrate to produce extended 2D-lattices [3] (Figures 1 & 2). These lattices could enable the creation of plasmonic metasurfaces with special optical properties, over large surfaces with a single process run.

While constructing lattices out of cross-shaped DNA origami, we found a way to fabricate DNA ribbons or tubes. At the moment, we are further studying the morphology and formation of these structures shown in figure 2.



↑ Figure 2. Atomic force microscope image of nanostructured ribbons formed by self-assembly of cross-shaped DNA origami, connected by blunt end stacking at the ends of the four arms. The inset shows a zoom of single origami on a Si-substrate, with some connection between them.



← Figure 3. Angle dependent transmittances of Fabry-Pérot cavities having R6G molecules or J-aggregates of TDBC embedded within them. Absorption spectra of the bare molecular films are shown on the right axis with scale at the top.

EFFECT OF MOLECULAR STOKES SHIFT ON POLARITON DYNAMICS

We have shown that the molecular Stokes shift plays a significant role in the relaxation of polaritons formed by organic molecules embedded in Fabry-Pérot cavities [4]. We studied cavities with 40 nm thick silver mirrors separated by a thin polymer film containing Rhodamine 6G (R6G) molecules, with a considerable Stokes shift, or J-aggregates of TDBC with a negligible Stokes shift. The dispersive transmittances of both cavities show clear Rabi splitting at the position of the molecular absorption, as shown in figure 3.

Our results suggest that in the case of R6G, the excitation of the upper polariton (UP) leads to a rapid decay to the dark states and localization of the energy into the fluorescing state of one of the molecules, from where the energy scatters into the lower polariton (LP) which then subsequently emits. This so-called radiative pumping is proven by the similarity between the photoluminescence (PL) spectra of the R6G cavity with the convolution of the R6G fluorescence with the cavity transmission spectrum, shown in figure 4. In contrast, for excitonic J-aggregates with a negligible Stokes shift, the fluorescing state does not provide an efficient relaxation gateway, as shown by the mismatch between the theory and the measured PL (Fig. 4). Instead, the relaxation is mediated by exchanging energy-quanta matching the energy gap between the dark states and lower polariton, into vibrational modes, i.e., so-called vibrationally assisted scattering.

For further studies, we have optimized our cavity geometries [5] and taken part in the theory development [6] in our collaboration group led by Prof. Tero Heikkilä (NSC/JYU).

Selected publications

[1] P. K. Parashar, S. Kinnunen, Timo Sajavaara, J. Jussi Toppari, Vamsi K. Komarala, Semicond. Sci. Technol. 36, 115013 (2021). DOI: 10.1088/1361-6641/ac2124

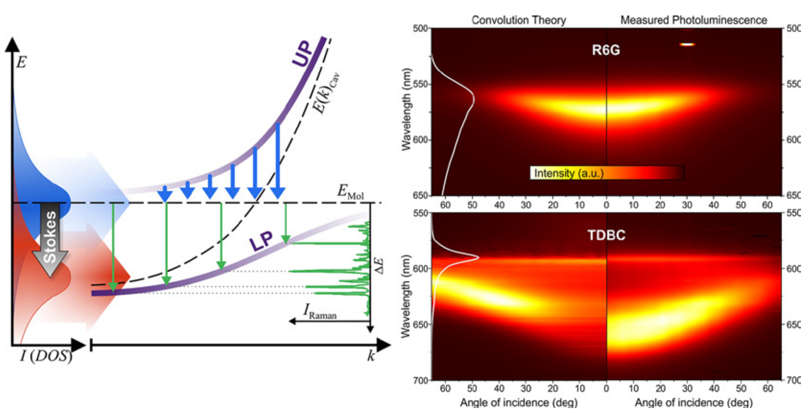
[2] Petteri Piskunen, Boxuan Shen, Adrian Keller, J. Jussi Toppari, Mauri A. Kostiainen, Veikko Linko, ACS Appl. Nano Mater. 4, 529–538 (2021). DOI: 10.1021/acsanm.0c02849

[3] Johannes M. Parikka, Karolina Sokołowska, Nemanja Markešević, J. Jussi Toppari, Molecules 26, 1502 (2021). Doi: 10.3390/molecules26061502

[4] Eero Hulkko, Siim Pikker, Ville Tiainen, Ruth H. Tichauer, Gerrit Groenhof, J. Jussi Toppari, J. Chem. Phys. 154, 154303 (2021). DOI: 10.1063/5.0037896

[5] Arpan Dutta, Ville Tiainen, J. Jussi Toppari, IOP SciNotes 2, 015205 (2021). DOI: 10.1088/2633-1357/abec2b

[6] Kalle S. U. Kansanen, J. Jussi Toppari, Tero T. Heikkilä, J. Chem. Phys. 154, 044108 (2021); doi.org/10.1063/5.0036905



← Figure 4. Relaxation pathways after an excitation of UP: the blue arrows show the relaxation into the dark states (blue distribution), followed by either relaxation into the fluorescing state (red distribution) and subsequent radiative pumping of LP; or direct vibrationally assisted scattering into LP directly from the dark states, shown as narrow green arrows. The green Raman spectrum shows the vibrational energies of the molecules calculated from the dark states. Measured PL of R6G and TDBC cavities are shown in the rightmost panel. The left panel shows the convolution of the transmittance of the cavity and the fluorescence spectrum of the molecule, which is shown separately on the left axis (white line).

HYBRID QUANTUM TECHNOLOGIES IN SILICON

Associate Professor Juha Muhonen

The development of quantum technologies is expected to revolutionize for example sensor applications and communication as well as lead to the actualization of a universal quantum computer. In our group we study the foundations of quantum technologies in silicon, the material that is already ubiquitous around us in computers, mobiles and all everyday electronics and hence provides unique possibilities for integrating quantum components with existing photonic or electronic circuits. The motivation for the 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. We are an experimental group located in the nanoscience center and our measurements methods are a combination of optical and electrical measurements, with heavy usage of cryogenic temperatures and nanofabrication.

www.jyu.fi/quantum-technologies

GROUP NEWS

The group (that was started in 2019) reached its peak size so far at the summer of 2021, after doctoral student Charles Rambo had joined the group in the spring 2021 and summer interns Pyry Runko and Milla Männikkö were present. Group photo above showing all the members at this point. Our measurement laboratory is now in full-time use. A major infrastructure important to the group that arrived in 2021 was the new ICP-RIE machine that was installed in the Nanoscience Center cleanroom.

↓ Figure 1. The group in the summer of 2021. From left: Pyry Runko, Antti Kanniainen, Charles Rambo, Milla Männikkö, Juha Muhonen, Teemu Loippo, Cliona Shakespeare, Joonas Nätkinniemi, and Henri Lyyra.

ROADMAP ON QUANTUM NANOTECHNOLOGIES

Group leader Muhonen was among a large group of international researchers producing a roadmap article about developments in key areas of quantum research in light of the nanotechnologies that enable them, and with a view to what the future holds. Materials and devices with nanoscale features are used for quantum metrology and sensing, as building blocks for quantum computing, and as sources and detectors for quantum communication. They enable explorations of quantum behaviour and unconventional states in nano- and opto-mechanical systems, low-dimensional systems, molecular devices, nano-plasmonics, quantum electrodynamics, scanning tunnelling microscopy, and more. The part written by Muhonen concentrated on how optomechanical devices can be used as quantum transducers between different quantum systems enabling a wholly new class of functionalities. [1]

ION IMPLANTATION DAMAGE IN SILICON OPTOMECHANICAL DEVICES

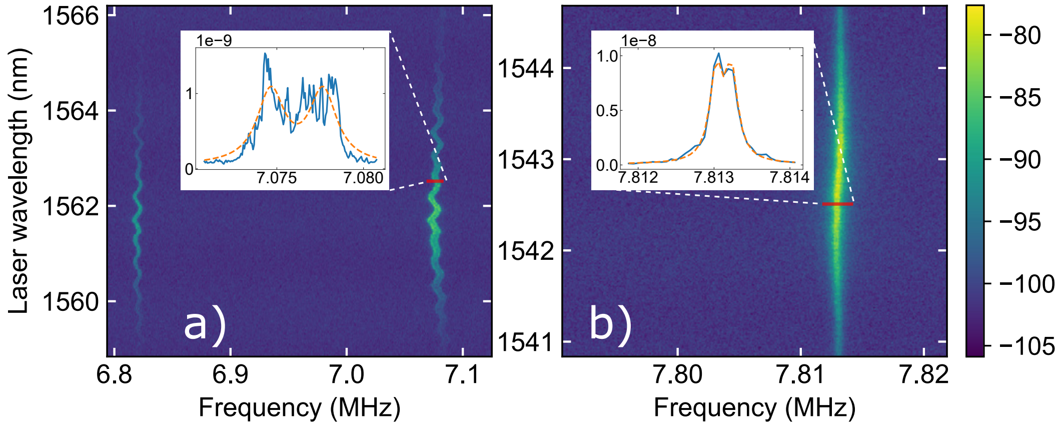
Ion implantation of silicon is a widely used method to modify the electronic properties of silicon by introducing defect atoms that donate electrons (or holes) that modify the electrical conductivity. For our research, ion implantation is the preferred method to introduce the defect atoms to be used as quantum bits or sensors into the silicon lattice. In this paper, we reported on studies where we noticed that the optical and mechanical properties of the silicon had changed considerably after the ion implantation. We also showed that the original properties could be recovered with proper annealing procedure. Although the ion implantation damage and the annealing procedure are well known effects, this was the first report on how the ion implantation damage affects suspended photonic crystal structures. We also reported on some unexplained anomalies in the samples before annealing. [2]

Selected publications

[1] A. Laucht *et al.*, Roadmap on quantum nanotechnologies, *Nanotechnology* **32**, 162003 (2021)

[2] C. Shakespeare, T. Loippo, H. Lyyra, and J.T. Muhonen, The effects of ion implantation damage to photonic crystal optomechanical resonators in silicon, *Materials for Quantum Technology* 1, 045003 (2021)

↓ Figure 2. Optomechanical spectrograms showing the mechanical motion imprinted on interferometer signal, colorscale intensity in dB. After ion implantation but before annealing the signals show strange oscillatory shape as a function of laser wavelength and a double-peak structure (left). After annealing the usual signal with a single peak is recovered (right).

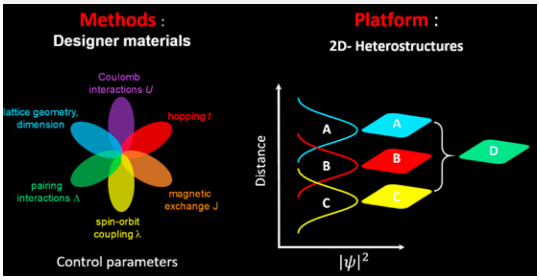


SYNTHETIC QUANTUM MATERIALS

Assistant Professor Kezilebieke Shawulienu

The synthetic quantum materials group studies artificial quantum materials using state-of-the-art scanning tunneling microscopy (STM) and molecular beam epitaxy (MBE) techniques. We generate insights into the most elusive and impactful materials that are exceedingly difficult to find intrinsically in isolated materials. The research in the group is extensively exploring various two-dimensional materials and their heterostructures to achieve new types of materials with engineered electronics properties. 2D materials can be easily combined in lateral and vertical heterostructures, providing an outstanding platform to engineer elusive quantum states of matter.

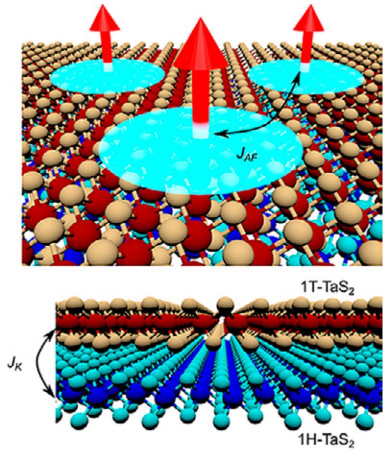
https://www.jyu.fi/science/en/physics/research/materials-physics/research-project-kezilebieke-shawulienu



↑ Figure 1. The control parameters for artificial materials synthesis (left). A platform for realizing new types of quantum materials (right).

ARTIFICIAL HEAVY FERMIONS IN A VAN DER WAALS HETEROSTRUCTURE

Heavy fermions systems are a paradigmatic class of strongly correlated materials. Heavy fermion physics is realized by exchange coupling between localized moments and conduction electrons giving rise to the well-known Kondo effect. In a Kondo lattice, this gives rise to a band with a heavy effective mass. However, this intriguing phenomenology has so far only been realized in compounds containing rare-earth elements with 4f or 5f electrons. Here the synthetic quantum materials group, in collaboration with Aalto University, realizes for the first-time heavy fermion physics in an artificial structure without the need of 4f or 5f rare-earth elements. We realize a designer van der Waals heterostructure where artificial heavy fermions emerge from the Kondo coupling between a lattice of localized magnetic moments and itinerant electrons in a 1T/1H-TaS2 heterostructure [1].



↑ Figure 2. Sketch of the heterostructure and scheme of the localized moments in 1T and itinerant electrons in 1H layers, respectively. The layers are coupled through exchange coupling JK.

This is achieved by incorporating the necessary physics (a lattice of localized moments Kondo coupled with itinerant electrons) in an artificial, engineered van der Waals heterostructure. This breakthrough result brings the control and tunability of van der Waals heterostructures to the enormous field of heavy fermion systems. Ultimately, this should allow the study of unconventional heavy fermion superconductivity, quantum criticality and non-Fermi liquid phases tunable by external gating and twist engineering.

Selected publications

[1] Viliam Vaňo, Mohammad Amini, Somesh C. Ganguli, Guangze Chen, Jose L. Lado, Shawulienu Kezilebieke & Peter Liljeroth, 'Artificial heavy fermions in a van der Waals heterostructure', Nature 599, 582–586 (2021). *https://doi.org/10.1038/s41586-021-04021-0*

COMPLEX MATERIALS

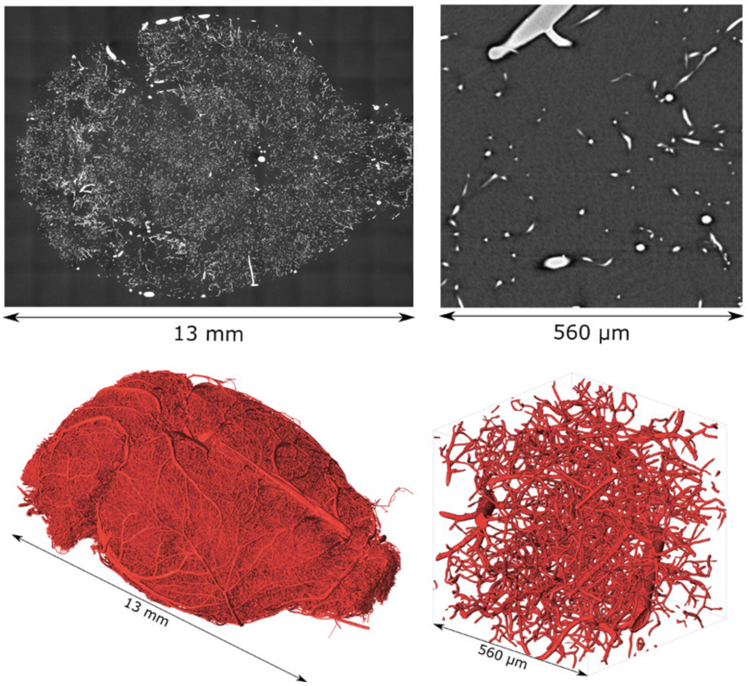
Professor Markku Kataja,
Senior Researcher Arttu Miettinen

The research scope of the group includes X-ray tomography and 3D image analysis, heterogeneous materials, their theoretical and numerical modelling, complex fluid mechanics and rheology, 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.

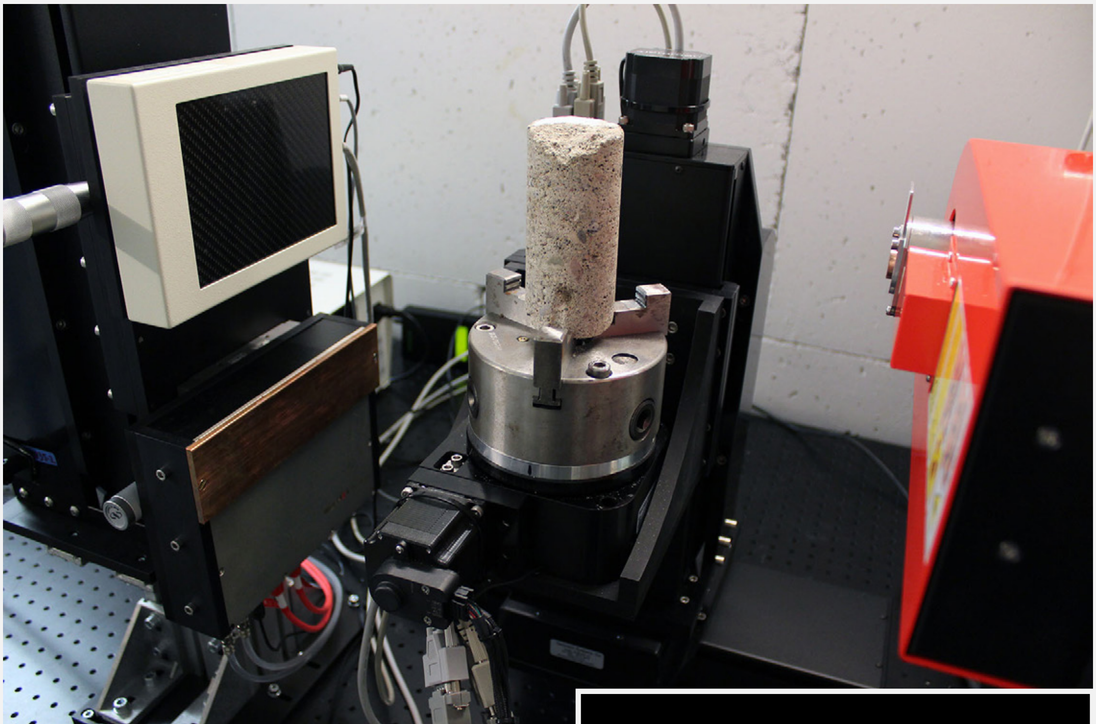
www.jyu.fi/physics/materials/complex-materials

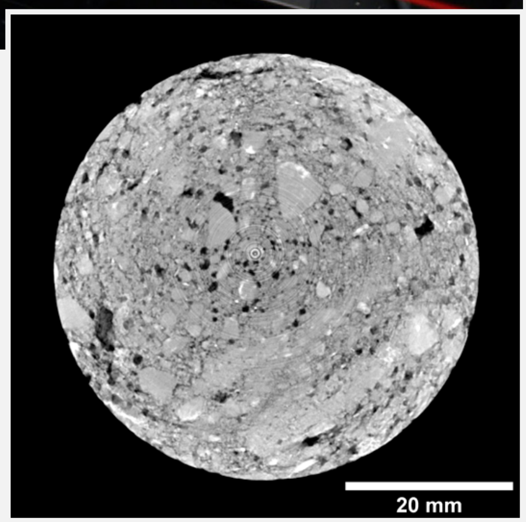
TERASCALE IMAGING OF CEREBRAL VASCULATURE IN POSTNATAL AND ADULT MICE

Together with collaborators from the University of Zürich (Switzerland), University hospital Zürich (Switzerland), Krembil research institute (Canada), Toronto university hospital (Canada), Leuven university (Belgium), Johannes Kepler university (Austria), Novartis (USA), ETH Zürich (Switzerland), and Paul Scherrer institute (Switzerland), the complex materials research group has developed a method [1] for tomographic imaging and analysis of vasculature in the entire mouse brain with unprecedented isotropic pixel size of 0.65 µm. The technique is based on mosaic tomographic imaging of corrosion cast cerebral vasculature and it is applicable to both postnatal and adult mice. The size of the resulting volumetric images, visualized in Figure 1, is in the terabyte-scale. These extremely large images are analyzed quantitatively using the in-house developed pi2 software that takes advantage of the leading supercomputers. The results can be applied in addressing the 3D structure of the entire cerebral vessel tree with higher precision than ever before.



← Figure 1: The top row shows cross-sectional tomographic slices through a mouse brain sample. The left panel shows the entire brain, and the right panel shows a small piece of the left image with full resolution. The bright regions are cross-sections of blood vessels. The bottom row shows 3D visualizations of the entire vessel tree (left) and a small region with full resolution (right).





↑ Figure 2: The current JTomo setup with the two detectors on the left-hand side, the flat panel being the topmost one and the Advacam pcd at the bottom. A cross-sectional slice through a concrete sample, acquired with the Advacam device, is also shown.

COMMISSIONING OF AN ENERGY-SENSITIVE PHOTON COUNTING DETECTOR

An energy-sensitive photon counting detector (pcd) has been installed and commissioned to the in house-built microtomograph JTomo. After this upgrade JTomo incorporates a two-camera system which contains a flat-panel detector (15 x 11 cm, 7 MP), and an Advacam Widepix L 1x10 pcd (14.1 x 1.4 cm, 0.7 MP). Widepix is based on Medipix3RX ASIC chips and it has a 1 mm thick CdTe-sensor. Combination of a microfocus X-ray source (40 – 150 kV, 75 W) and CdTe-pcd enables energy selective X-ray imaging in a wide energy range from 8 keV to 150 keV. Widepix has one or two energy thresholds which can be utilized to select the energy window for imaging. The first tomography scans were performed by using Widepix and results were of good quality as shown in Figure 2. In the future, energy information will be utilized in the development of new materials analysis methods, for example material identification based on multi-energy imaging.

Selected publications

[1] Thomas Wälchli, Jeroen Bisschop, Arttu Miettinen, et al. Hierarchical imaging and computational analysis of three-dimensional vascular network architecture in the entire postnatal and adult mouse brain. Nature Protocols 16 (2021).

COMPUTATIONAL NANOSCIENCE

Professor Hannu Häkkinen

Nanoparticles are everywhere but we do not see them nor do we understand them well. That is why fundamental research into their physical, chemical and biological properties is needed. Our group (Figure 1) uses and develops multiple computational methods and machine learning to investigate metal-based and organic nanoparticles whose atomic structure is known or can be modelled to **atomic precision**.

https://r.jyu.fi/zA7

Currently we want to understand:

1. How clustering of organic molecules initiates formation of aerosol particles?
2. How metal nanoparticles work as thermocatalysts and electrocatalysts?
3. How gold-based nanoparticles work as sensors in a biological environment?
4. How gold-based nanoparticles work as targeted carriers for cancer drugs?

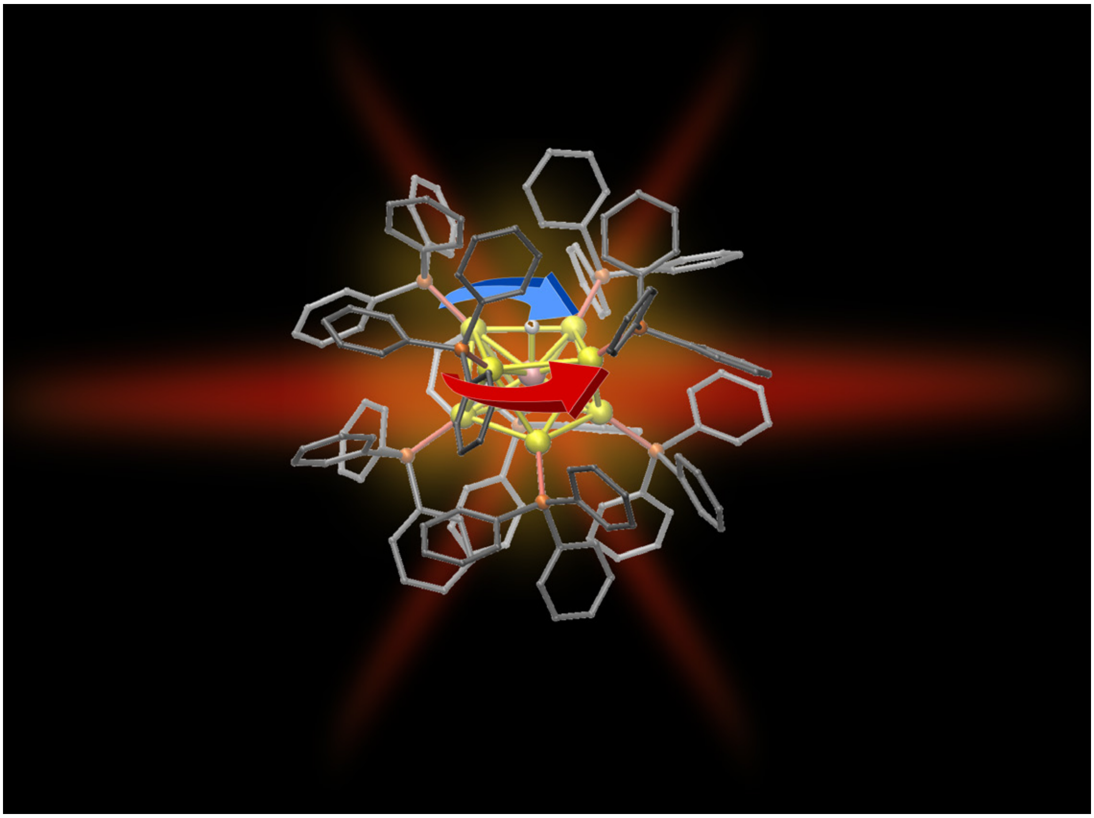
↑ Figure 1. The computational nanoscience group. Back row, from left: Juha Tiihonen, Sami Malola, Lluis Nocete Pladevall, Omar Lopez Estrada, Maria Francisca Matus, Kyunglim Pyo. Front, from left: Antti Pihlajamäki, Hanna Jääskö, Noora Hyttinen, Hannu Häkkinen, Nisha Mammen, Maryam Sabooni

MAGNETICALLY INDUCED CURRENTS AND AROMATICITY IN LIGAND-STABILIZED GOLD-BASED SUPERATOMS.

Understanding magnetically induced currents (MICs) in aromatic or metallic nanostructures is crucial for interpreting local magnetic shielding and NMR data (Figure 2). Direct measurements of the induced currents have been successful only in a few planar molecules but their indirect effects are seen in NMR shifts of probe nuclei. Recently, we have implemented a numerically efficient method to calculate gauge-including MICs in the formalism of auxiliary density functional theory [1]. We analyzed the currents in two experimentally synthesized gold-based, hydrogen-containing ligand-stabilized nanoclusters $[HAu_9(PPh_3)_8]^{2+}$ and $[PtHAu_8(PPh_3)_8]$+. Both clusters have a similar octet configuration of Au(6s)-derived delocalized "superatomic" electrons. Surprisingly, Pt-doping in gold increases the diatropic response of the superatomic electrons to an external magnetic field and enhances the aromaticity of $[PtHAu_8(PPh_3)_8]^{+}$. This is manifested by a stronger shielding of the hydrogen proton in the metal core of the cluster as compared to $[HAu_9(PPh_3)_8]^{2+}$, causing a significant upfield shift in agreement with experimental proton NMR data measured for these two clusters. Our method allows the determination of local magnetic shielding properties for any component in large 3D nanostructures, opening the door for detailed interpretation of complex NMR spectra.

Selected publications

[1] O. Lopez-Estrada, B. Zuniga-Gutierrez, E. Selenius, S. Malola and H. Häkkinen, "Magnetically induced currents and aromaticity in ligand-stabilized Au and AuPt superatoms", Nature Comm. 12, 2477 (2021).



↑ Figure 2. Visualization of an atomically precise gold nanoparticle where the metal atoms are stabilized by an organic ligand layer. When placed in a magnetic field, the valence electrons in the metal atoms form collective circulating currents (blue and red arrows) in a plane perpendicular to the magnetic field. There are two opposing components in this current: diatropic (classical, from Lenz law, inducing an opposing magnetic field) and paratropic (quantum-mechanical) ones. The method introduced in ref. 1 allows for numerically effective calculation, analysis, and visualization of these currents.

CONDENSED MATTER THEORY

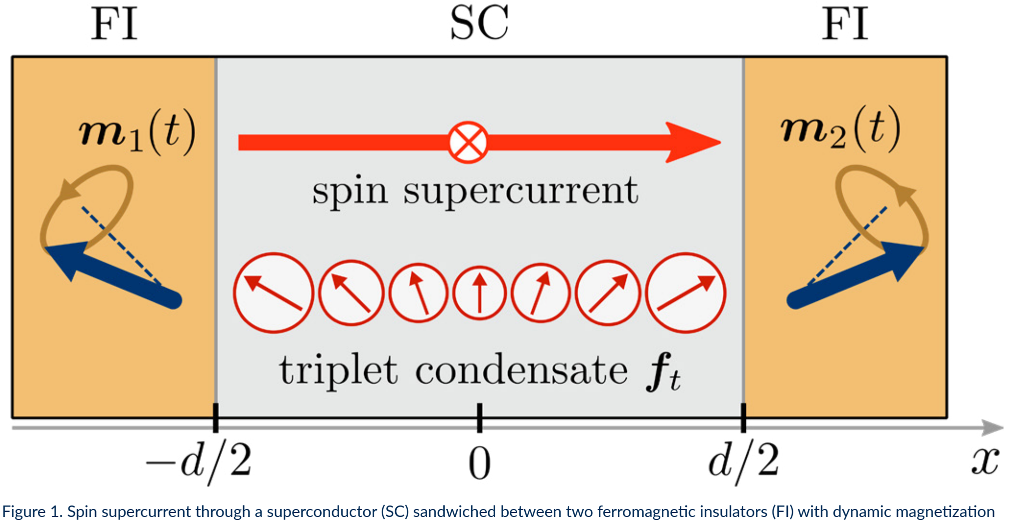
Professor Tero Heikkilä

We study 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 constructing and characterizing the phenomenological low energy theory of quantum systems relevant for the phenomena to be described. In each project we collaborate with world-leading experimental groups and our goal is to predict observables and to find out the key elements underlying the previous measurements.

https://www.jyu.fi/science/en/physics/research/materials-physics/condensed-matter-theory

MAGNETIZATION DYNAMICS IN THE PRESENCE OF SUPERCONDUCTORS: ROLES OF SPIN SUPERCURRENT AND HIGGS MODES

The key aim in spintronics is to control magnetization configurations with applied electronic currents. Superconducting spintronics aims at finding operation modes where this control could be realized with minimal dissipation. We have studied superconductor-specific phenomena contributing to the magnetization dynamics. We showed how spin supercurrents link to the rotation of spin triplet superconducting pairing in systems with non-collinear magnetization dynamics, and how the presence of these spin supercurrents affects the magnetization dynamics [1]. In most cases the pair potential describing the superconducting state can be considered static even when the magnetization is dynamic. This fails when the magnetization frequency (times Planck constant) is close to the superconducting gap energy. In this case it is possible to excite the collective Higgs amplitude mode of superconducting order parameter. We have identified the conditions for finding the coupling between magnetization dynamics and Higgs modes and predicted how this coupling can be experimentally accessed [2].



↑ Figure 1. Spin supercurrent through a superconductor (SC) sandwiched between two ferromagnetic insulators (FI) with dynamic magnetization

DIRECTLY PROBING THE CHIRALITY OF MAJORANA EDGE STATES

One of the suggested platforms for topological quantum computing is that of Majorana states. Recently the interest has been shifted from the zero-dimensional Majorana modes at ends of nanowires to realizing one-dimensional chiral Majorana modes at the edges of two-dimensional superconductor/ferromagnet structures. There are experimental indications of the presence of such edge states in tunneling spectra. However, such experiments cannot directly identify the chirality of the states as evidence of their Majorana character. We suggest a scheme to probe the chirality using polarization selective photon absorption [3].

SUPERCONDUCTOR/FERROMAGNET SYSTEMS AS NON-RECIPROCAL ELEMENTS

The goal of the *SUPERTED FET Open* project is to realize the world's first superconducting thermoelectric detector of electromagnetic radiation, based on junctions between superconducting and magnetic elements. The key phenomenon behind the thermoelectricity is the non-reciprocity of the contact between these two systems, as the broken spin symmetry can be directly connected to the broken electron-hole symmetry. In a recent work combining theory and experiments, we have shown how these systems operate analogously to semiconductor diodes, enabling features like current rectification [4,5]. The major difference is that superconductors have much smaller energy gaps than semiconductors, which is why such superconductor tunnel diodes can be used in different energy regimes, and especially at low, sub-Kelvin temperatures relevant for many quantum technology initiatives.

MAGNOMECHANICS IN SUSPENDED MAGNETIC BEAMS

Cavity optomechanics has recently had tremendous success in describing non-linear interaction between light and motion, and in probing the boundaries of quantum and classical worlds. We propose a scheme to realize magnomechanics in suspended magnetic beams [6]. In such a system, the vibrations of the beam and its ferromagnetic resonance mode are coupled, realizing a magnetic analog of an optomechanics. We find an analytical expression for the magnomechanical coupling rate together with an input-output framework for understanding future measurements.

QUANTUM KINETIC THEORY IN DISORDERED SYSTEMS WITH SPIN-ORBIT INTERACTION

The most robust way of studying nonequilibrium transport phenomena in disordered conductors proceeds via the non-linear sigma-model Keldysh action, which describes diffusion of electrons as a Goldstone mode associated with a symmetry of the problem. It encompasses the influence of strong disorder while retaining the possibility of describing effects far from equilibrium, fluctuations, and symmetry broken systems such as superconductivity. What has been so far missing in this framework is the possibility for treating consequences of strong spin-orbit interactions in magnetoelectric effects coupling spin and charge transport. We have solved this issue by suggesting [7] a generalization including the necessary terms allowed by symmetries in the Lagrangian. This provides a consistent method for studying spin Hall and spin swapping effects in the superconducting state, along with the plethora of effects only found in the superconducting state, such as the superconducting diode effect. Prior to our work the transport theory was formulated only in the Ginzburg-Landau regime close to the critical temperature.

TOPOLOGICAL POLARIZATION, DUAL INVARIANTS, AND SURFACE FLAT BANDS IN CRYSTALLINE INSULATORS

We describe a crystalline topological insulator (TI) phase of matter that exhibits spontaneous polarization in arbitrary dimensions [8]. The bulk polarization response is constructed by coupling the system to geometric deformations of the underlying crystalline order, represented by local lattice vectors—the elasticity tetrads. This polarization results from the presence of (approximately) flat bands on the surface of such TIs. These flat bands are a consequence of the bulk-boundary correspondence of polarized topological media, and contrary to related nodal line semimetal phases also containing surface flat bands, they span the entire surface Brillouin zone.

Selected publications

[1] R Ojajärvi, FS Bergeret, MA Silaev, TT Heikkilä, *arXiv:2107.09959*.

[2] Y Lu, R Ojajärvi, P Virtanen, MA Silaev, TT Heikkilä, *arXiv:2108.06202*.

[3] Y Lu, P Virtanen, TT Heikkilä, *arXiv:2111.05707*.

[4] E Strambini, M Spies, N Ligato, S Ilic, M Rouco, C González Orellana, M Ilyn, C Rogero, FS Bergeret, JS Moodera, P Virtanen, TT Heikkilä, F Giazotto, *arXiv: 2109.01061*, Nature Commun. (in press).

[5] S Ilić, P Virtanen, TT Heikkilä, FS Bergeret, arXiv:2109.10201, Phys. Rev. Appl. (in press).

[6] KSU Kansanen, C Tassi, H Mishra, MA Sillanpää, TT Heikkilä, *Phys. Rev. B 104, 214416 (2021).*

[7] P Virtanen, FS Bergeret, IV Tokatly, *Phys. Rev. B 104, 064515 (2021)*.

[8] J Nissinen, TT Heikkilä, GE Volovik, *Phys. Rev. B 103, 245115 (2021)*.

QUANTUM MANY-BODY THEORY

Professor Robert van Leeuwen

The quantum many-body theory group develops new theoretical methods to study many-body quantum systems in and out of equilibrium. The main approaches being developed are diagrammatic perturbation theory for non-equilibrium systems and the further development of time-dependent density functional theory. The main applications of these methods are for the electronic structure theory of nanosystems. Recent developments have focused on coupled electron-boson systems such as the electron-phonon and electron-photon interactions and the development of methods for quantum lattice systems for the study of strongly correlated materials. The latter is an ongoing new research line which was initiated as a part of a sabbatical leave at Sorbonne University in Paris, France.

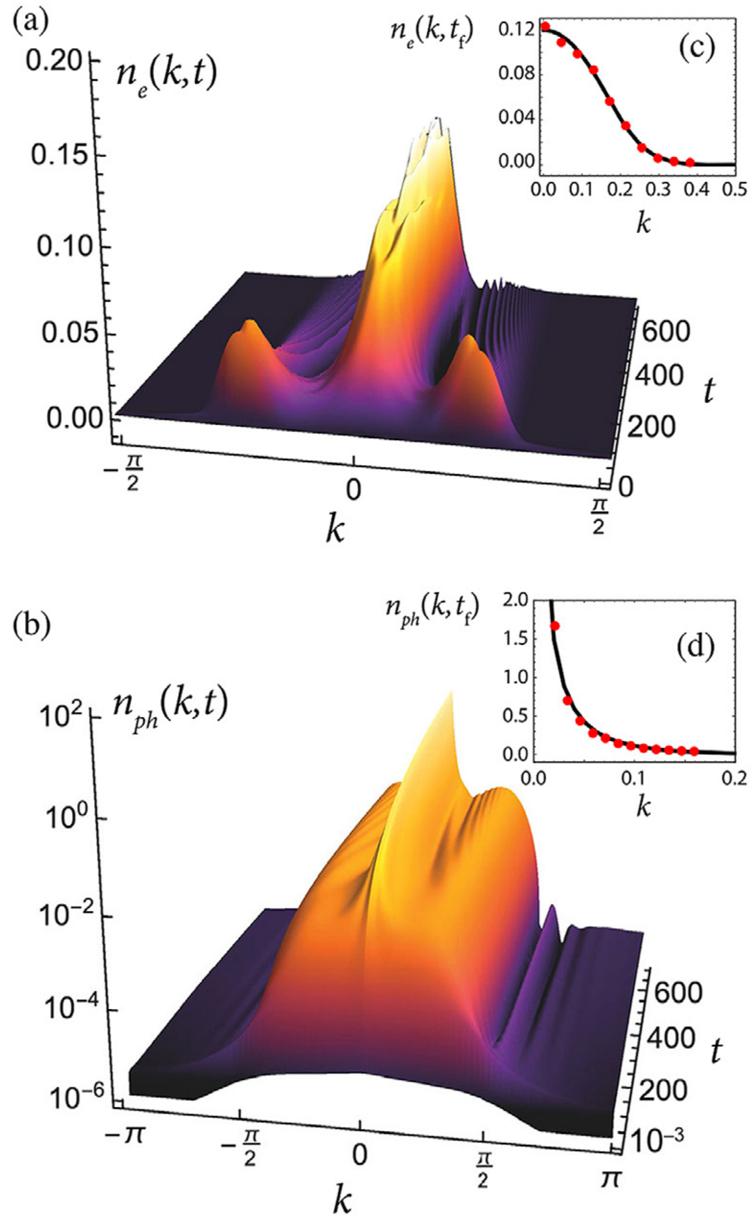
https://www.jyu.fi/science/en/physics/research/materials-physics/quantum-many-body-theory/research

ULTRAFAST ELECTRON-BOSON DYNAMICS

The interaction of electrons with quantised phonons and photons underlies the ultrafast dynamics of systems ranging from molecules to solids, and it gives rise to a plethora of physical phenomena experimentally accessible using time-resolved techniques. Many-body Green's function methods offer an invaluable interpretation tool since scattering mechanisms of growing complexity can be selectively incorporated in the theory. Currently, however, real-time Green's function simulations are either prohibitively expensive due to the *cubic* scaling with the propagation time or do neglect the feedback of electrons on the bosons, thus violating energy conservation. We developed a computationally efficient Green's function scheme which overcomes both limitations. The numerical effort scales *linearly* with the propagation time while the simultaneous dressing of electrons and bosons guarantees the fulfilment of all fundamental conservation laws. This was used to perform a real-time study of the phonon-driven relaxation dynamics in an optically excited narrow band-gap insulator, highlighting the non-thermal behaviour of the phononic degrees of freedom. Our formulation paves the way to first-principles simulations of electron-boson systems with unprecedented long propagation times [1].

DENSITY-FUNCTIONAL THEORY AND ITS MATHEMATICAL FOUNDATION FOR QUANTUM LATTICE SYSTEMS

Quantum lattice systems play a key role in the study of strongly correlated systems. Its paradigm model is the Hubbard system which displays complex many-body behaviour as exemplified by the Mott-Hubbard transition. The study of such systems has received intense international efforts in the study of so-called strongly correlated materials and the study of non-conventional superconductivity. The key issue is that interactions are so strong that conventional perturbation methods for these systems are no longer within their range of validity and non-perturbative methods are called for. We therefore made a renewed effort to advance density functional methods for this goal. However, as the basic methodology was originally developed for continuum systems, we thoroughly reviewed its rigorous foundation in collaboration with the department of mathematics of the university of Innsbruck, Austria. We showed that there are surprising new aspects for the lattice systems, related to so-called non-unique v-representability, and we managed to derive some key foundational results on which future developments can be built [2].



↑Figure 1. Relaxation of conduction electrons (a) and acoustic phonons (b) in a two-band semi-conductor model excited with a laser pulse of optical frequency [1]. Electrons are coupled to a branch of acoustic phonons. Insets (c) and (d) depict e and ph populations at the end of the propagation which can be well fitted with the Fermi-Dirac and the Bose-Einstein distributions.

Selected publications

[1] Daniel Karlsson, Robert van Leeuwen, Yaroslav Pavlyukh, Enrico Perfetto, Gianluca Stefanucci, *Fast Green's function method for Ultrafast Electron-Boson Dynamics*, Physical Review Letters, **127**, 036402 (2021)

[2] Markus Penz and Robert van Leeuwen, *Density-functional theory on graphs*, Journal of Chemical Physics, **155**, 244111 (2021)

LOW-DIMENSIONAL NANOMATERIALS MODELING

Professor Pekka Koskinen

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.

www.jyu.fi/physics/materials/low-dimensional-nanomaterials-modeling

ULTRAFLIMSY GRAPHENE TURNED ULTRASTIFF BY OPTICAL FORGING

The atomically thin structure of graphene makes it ultraflimsy. However, in a collaboration with an experimental group from the Nanoscience Center, we demonstrated how an experimental technique called optical forging can turn graphene from ultraflimsy to ultrastiff [1]. Nanoindentation measurements revealed that the bending stiffness of graphene increased up to five orders of magnitude compared to pristine graphene, which is a new world record. Our thin-sheet elasticity modeling of corrugated elastic membranes suggests that the stiffening happens on both the micro- and nanometer scales.

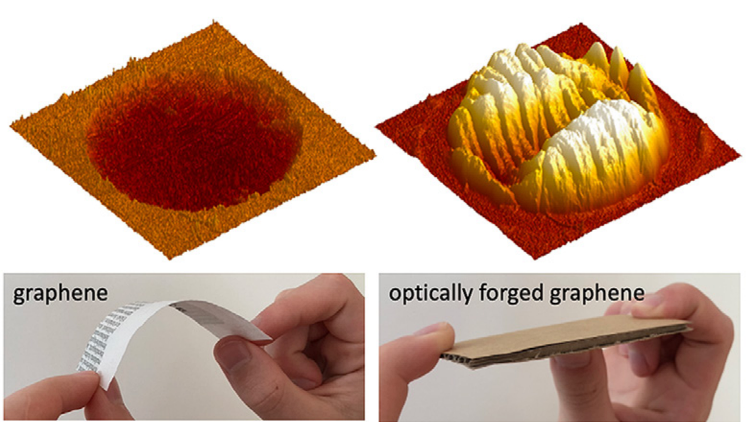
LIMITS OF LATERAL EXPANSION IN TWO-DIMENSIONAL MATERIALS

The flexibility of two-dimensional (2D) materials enables ripples that cause lateral contraction, shrinking of the material boundary. However, it has been unknown whether 2D materials can also *expand* laterally. Using thin sheet elasticity theory, sequential multiscale modeling, and structure modification by line defects, we were able to demonstrate that the lateral expansion is inevitably limited by the onset of rippling [2]. The maximum lateral expansion is proportional to defect density and the square of elastic thickness and remains well below 1% for typical material parameters.

Selected publications

[1] V.-M. Hiltunen, P. Koskinen, K. K. Mentel, J. Manninen, P. Myllyperkiö, M. Pettersson, and A. Johansson, *2D materials and applications* **5**, 49 (2021)

[2] P. Koskinen, *Phys. Rev. B.* **5**, 091001 (2021) (Letter)



← Figure 1. Atomic force microscopy images of the topography of pristine graphene (left) and optically forged graphene (right). (The vertical scale is enhanced by a factor of six.) Optical forging creates corrugations that increase the bending stiffness dramatically.

SUPERCONDUCTING SPINTRONICS

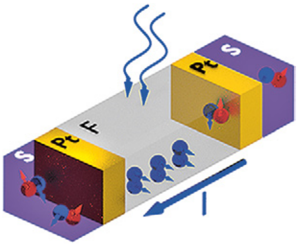
Academy Research Fellow Mihail Silaev

We study transport and dynamical properties of correlated electron systems such as superconductors and their interaction with quantum fields such as photons and magnons. The group functioned during 2016–2021 and produced about 40 papers in leading journals including several high-impact ones. Group member PhD student Risto Ojajärvi, shared with the group of prof. Tero Heikkilä, has prepared his thesis and will defend on 8 April 2022. Group leader Mikhail Silaev has moved to the newly organized *Institute of advanced study, Tampere University*. During the year 2021 we have produced among others three papers in high-impact journals described below.

https://www.jyu.fi/science/en/physics/research/materials-physics/superconducting-spintronics

PHOTO-INDUCED SPIN-TRIPLET SUPERCONDUCTIVITY

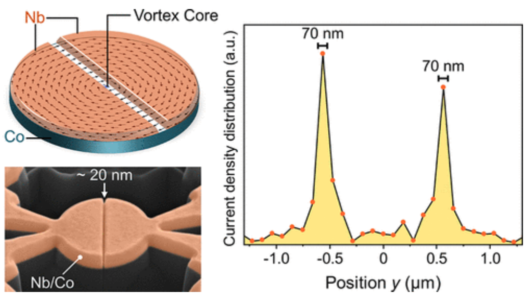
Dynamic states offer extended possibilities to control the properties of quantum matter. Here we demonstrate a class of systems which feature the dynamic spin-triplet superconducting order stimulated by light. The effect is based on the interplay of ferromagnetism, interfacial spin-orbital coupling and the motion of Cooper pairs induced by the electromagnetic field. We hope that our results will guide future experimental investigations of the dynamic superconducting orders and new generations of the superconducting light-controlled electronics. [1]



↑ Figure 1. Schematic picture of the system considered consisting of the superconductor, ferromagnet and the heavy metal Pt. The Cooper pairs are shown by spheres with arrows which represent spins. Spin-singlet Cooper pairs in superconducting electrodes have opposite spin directions and spin-triplet Cooper pairs in ferromagnet interlayer have parallel spins.

SUPERCONDUCTING TRIPLET RIM CURRENTS IN A SPIN-TEXTURED FERROMAGNETIC DISK

We have developed nanostructured Josephson junctions with highly controllable spin texture, based on a disk-shaped Nb/Co bilayer (Fig.2). Here, the vortex magnetization of Co and the Cooper pairs of Nb conspire to induce long-range triplet (LRT) superconductivity in the ferromagnet. Surprisingly, the LRT correlations emerge in highly localized (sub-80 nm) channels at the rim of the ferromagnet, despite its trivial band structure. We show that these robust rim currents arise from the magnetization texture acting as an effective spin–orbit coupling, which results in spin accumulation at the bilayer–vacuum boundary. It results in the two edge channels transmitting Josephson current (Fig.2). Lastly, we demonstrate that by altering the spin texture of a single ferromagnet, both 0 and π channels can be realized in the same device. [2]



↑ Figure 2.

DYNAMICAL EXCHANGE COUPLING MEDIATED BY THE SPIN SUPERCURRENT

See the description in the Condensed matter theory group results by prof. T.T. Heikkilä [3]

Selected publications

[1] I. V. Bobkova, A. M. Bobkov, and M. A. Silaev, "Dynamic Spin-Triplet Order Induced by Alternating Electric Fields in Superconductor-Ferromagnet-Superconductor Josephson Junctions",
Phys. Rev. Lett. 127, 147701. *JYU Press Release*.

[2] R. Fermin, D. van Dinter, M. Hubert, B. Woltjes, M. Silaev, J. Aarts, and K. Lahabi, arXiv:2110.13035, Nano Lett. 2022,
https://doi.org/10.1021/acs.nanolett.1c04051

[3] R Ojajärvi, FS Bergeret, MA Silaev, TT Heikkilä, arXiv:2107.09959, acc. to Phys. Rev. Lett.

ACCELERATOR LABORATORY

Professor Paul Greenlees
Head of Accelerator Laboratory

As Head of the Accelerator Laboratory (JYFL-ACCLAB), when recollecting the events of 2021, first and foremost in my mind is the unfortunate accident which occurred within the laboratory in April. The accident involved part of the helium purification and recycling system at the IGISOL facility and resulted in the injury of a member of staff, who has since recovered. The actions of the cyclotron operators who were on duty at the time are to be commended, administering first aid and co-ordinating with the emergency services and local staff.

Following on from the somewhat chaotic situation in 2020, with a scheduled shutdown followed by an enforced shutdown due to the COVID-19 pandemic, in 2021 the operations of JYFL-ACCLAB slowly began to return to something close to normal. The K130 delivered 5 952 hours of beam to experiments, with average per year from 1996 onwards being 6 432 hours. Close to seven weeks in 2021 were allocated for routine maintenance of the cyclotron and infrastructure of the laboratory. A total of 47 different "runs" were carried out, mainly distributed between Nuclear Spectroscopy (43%), RADEF and industrial applications (33%) and IGISOL (23%). The fraction used by IGISOL was lower than usual due to some consequences of the accident. Overall, the reliability of the K130 and Pelletron accelerators, ion sources and control system of JYFL-ACCLAB were at an exceptionally high level. Thanks for this result must once again go to the highly dedicated and excellent team of technical staff from the accelerator group and mechanical and electrical workshops.

The numbers given above are even more remarkable, when it is remembered that for most of 2021, travel and other restrictions such as testing and enforced quarantine due to the COVID-19 pandemic were still in place**.** Perhaps most emblematic of the desperate need to use the services of JYFL-ACCLAB can be seen in the fact that many of the industrial users of the RADEF facility were willing to pay the expense of having their staff in quarantine for two weeks in advance of carrying out an irradiation, which may have lasted only a few days. Unfortunately, many of the international research groups using JYFL-ACCLAB do not have the resources available to allow for such arrangements. This has led to the local research teams having to stretch an extra mile in order to carry out the experiments and maintain the high level of productivity at the facility. The efforts of all the research staff in the facility are hugely appreciated.

As usual, a number of projects either continued, ended or started in 2021. The ENSAR2 Integrating Activity to provide access to the facility for users in the field of Nuclear Structure, Nuclear Reactions and Applications of Nuclear Science ended on the 31st August 2021. A new application to Horzion Europe for similar access to European accelerator facilities (EURO-LABS) was submitted in late October. The latest addition to the list of EU access programs at JYFL-ACCLAB was the RADNEXT Integrating Activity (RADiation facility Network for the Exploration of effects for indusTry and research) which started on 1st June 2021. In May, the Academy of Finland granted funding for a new project "PANTHER" – aimed at better understanding of the actinide elements and an excellent example of collaboration between the in-house experimental and theory groups. The project is led by Markus Kortelainen and Iain Moore. Despite the COVID-19 restrictions, towards the end of the year in October, it was possible to host a workshop and hands-on training in "Advanced Techniques for the Production and Study of Actinides at JYU" for the younger researchers in the LISA Marie Sklowdowska-Curie Action Innovative Training Network.

Work continued to improve the access to the facilities and services for the users of the laboratory, with the development of a new online system for proposal submission built upon the Vasara platform in a project realised by the University Division of Policy and Planning. In future the system will be expanded to help deal with radiation safety and induction training.

Two technical milestones can also be highlighted – in summer, the first plasma was ignited in the innovative ECR ion source CUBE. CUBE is a major component of the research carried out within the Academy of Finland project led by Hannu Koivisto "The effect of a magnetic field configuration on the performance of minimum-B ECR ion sources". The first ion beams were produced in November 2021 and in November and December ion beams of multiply charged argon, helium and krypton were successfully extracted. The second milestone was the start of the installation of MORA (Matter's Origin from RadioActivity) experiment at the IGISOL facility in November 2021. MORA will be searching for a signature of CP violation in the nuclear beta decay of radioactive nuclei produced at IGISOL. MORA is supported by the French Agence Nationale de la Recherche (ANR) and Région Normandie. The MORA collaboration consists of GANIL, LPC Caen, IJCLab, JYFL-ACCLAB, KU Leuven, CERN-ISOLDE and IFIC, as partner laboratories. The MORA apparatus will eventually move back to GANIL once the DESIR installation is available, to pursue its scientific program from 2027 onwards.

Last but not least, actions were taken to address the future of the laboratory, with initial meetings and discussions on the scientific strategy of JYFL-ACCLAB. As part of this work, a consultant was hired to make an investigation or "market survey" of the needs of the radiation effects community for ion beams with higher energies to test electronic components. The results of this survey will be used to inform the decision of whether to proceed with the planning of a new cyclotron facility. The future strategy of JYFL-ACCLAB will be presented to the International Advisory Board in 2022.

NUCLEAR SPECTROSCOPY

Professor Paul Greenlees
Associate Professor Tuomas Grahn
Senior Researchers Juha Uusitalo and Janne Pakarinen
Postdoctoral Researcher Andrew Briscoe

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 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 and the ISOLDE Decay Station at ISOLDE, CERN, in the AGATA collaboration to build a gamma-ray tracking array and in the SUPER-FRS, HISPEC/DESPEC and SHE collaborations which form part of the NuSTAR pillar of FAIR in Germany.

In 2021, the group continued to focus on the experimental in-beam spectroscopy campaign with the JUROGAM 3 array of germanium detectors at the MARA separator. Despite the continuing difficult situation with COVID-19, the group was able to carry out a comprehensive experimental program. A total of 115 days of beam time were used in eleven separate experiments at the MARA vacuum-mode spectrometer. The group members were co-authors in 22 peer-reviewed journal publications.

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

↑ Figure 1: The Nuclear Spectroscopy Group

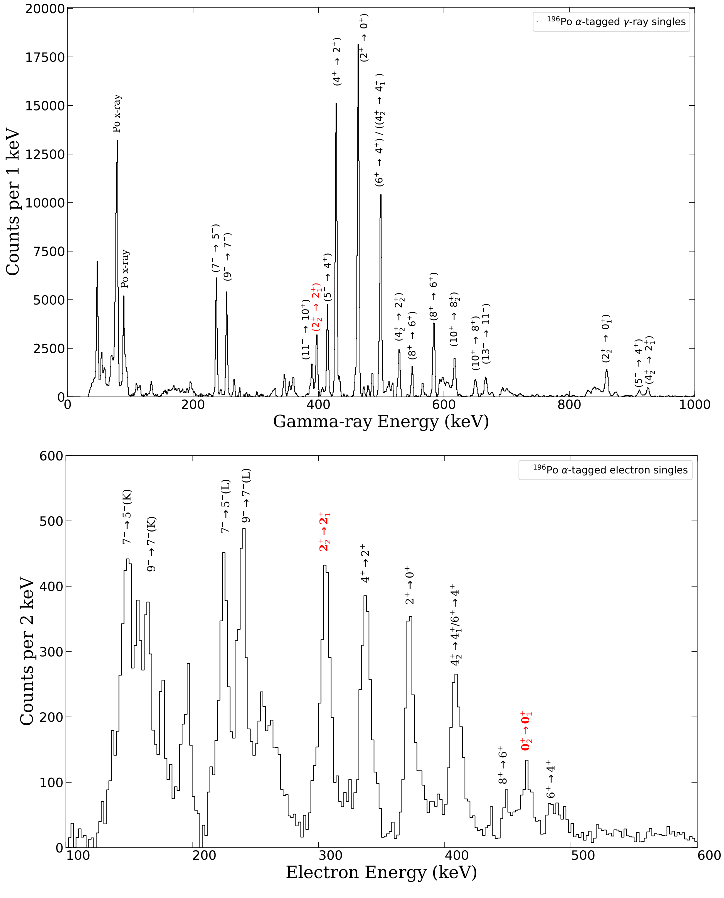
Following the somewhat exceptional year 2020, in 2021 the work of the Nuclear Spectroscopy group eventually came to be something close to normal, especially towards the end of the year. In late 2020, due to the COVID restrictions, the group had already started to prioritise experiments with mainly in-house spokespersons and with fewer collaborators. In the early part of 2021, this trend continued as the pandemic was still raging and travel restrictions were in place. As many of the experiments of the Nuclear Spectroscopy group last for a week or even two weeks, having to cover the shifts with only local staff was rather demanding for the group. The situation meant that researchers from the IGISOL group participated in Nuclear Spectroscopy group experiments and vice versa, a very good development. After the summer break in the July, the experiments in August and until the end of the year allowed for visitors, closer to our normal mode of operation.

RESEARCH ACTIVITIES

In recent years, the research of the Nuclear Spectroscopy group has been centered around experiments at the MARA vacuum-mode recoil separator, which has operated very reliably and has been proven to be a competitive device for studies of neutron-deficient nuclei. MARA has a very high-quality suite of silicon, germanium and scintillator detectors at the focal plane of the separator to enable the study of the decay properties of implanted nuclei and has already produced a number of new isotopes. Arrays of detectors such as JUROGAM 3 can be placed at the target position in order to study the structure of excited states in nuclei produced by reactions and separated by MARA.

One of the main drivers behind the development of MARA was to make improved studies of nuclei with similar numbers of protons and neutrons or N=Z nuclei, where isospin symmetry effects can be enhanced. As in earlier years, many of the experiments at MARA were focused on such nuclei. These experiments are extremely challenging and many of the nuclei have never been studied before or very little information is known about them. In many cases, the available information is from previous experiments carried out by the Nuclear Spectroscopy group using the RITU gas-filled separator, which was not originally designed for such studies. Over the years, in collaboration with overseas research groups, the instrumentation and methods available have been developed to allow much improved studies of N=Z nuclei (see, for example, the novel scintillator detector reported in the 2020 Annual Report). In 2021, studies of isospin symmetry and nuclear structure were made in the nuclei ^{70,71}Kr, ^{78}Zr and attempted in ^{96}Cd. In the case of ^{70}Kr, the newly developed technique of double beta-decay tagging was used in order to try to find the excited T=1 isobaric analogue states of ^{70}Kr (and ^{70}Br). The experiment worked well and candidate transitions were observed. Due to the fact that the RITU gas-filled separator has been out of use for several years and that the new focal plane detection system has not been commissioned, along with the fact that the JUROGAM 3 array was installed at MARA, it was decided to run some experiments originally planned for RITU at MARA. Whilst MARA was designed mainly for studies of nuclei with masses of around 100 and below, RITU was designed for studies of heavy nuclei with masses of around 150 and above. It has therefore been somewhat satisfying to learn that both separators can perform over a much wider range. Indeed, the performance of MARA for some reactions leading to heavier nuclei is even better than that of RITU. In 2021, experiments were made to study the heavy nuclei ^{191,192}Bi and ^{213}Ac on the theme of shape co-existence.

In 2021, the SAGE spectrometer designed for simultaneous detection of gamma rays and internal conversion electrons, was installed at the target position of MARA for the first time. SAGE was originally designed for studies of very heavy and superheavy nuclei, but has now been shown to be a world-leading device for studies of nuclei with masses in the region of 150-200. Many of these nuclei exhibit shape co-existence and can have enhanced electric monopole transitions which result in the emission of internal conversion electrons. The detection of internal conversion electrons in SAGE is enabled with the aid of a high-voltage (HV) barrier to suppress delta electrons produced when the beam impinges on the reaction target. Operation of the HV barrier is made much simpler in MARA as it operates in vacuum mode rather than the gas-filled mode of RITU, where SAGE has previously been installed. The SAGE campaign was very successful with a series of experiments to study ^{185}Hg, ^{196}Po and ^{190}Pb. An example of the quality of data obtained in the SAGE campaign can be seen in figure 2 below. The figure shows the internal conversion electrons and gamma rays emitted from ^{196}Po and detected in the SAGE spectrometer. The recoil-decay tagging technique is used, whereby the characteristic alpha decay of ^{196}Po can be exploited to isolate the gamma rays or electrons emitted from a particular nucleus. The upper panel shows the recoil-decay tagged spectrum of gamma rays from ^{196}Po and the lower panel shows the equivalent spectrum of internal conversion electrons.



← Figure 2: Recoil-decay tagged gamma ray (upper panel) and internal conversion electron spectra (lower panel) from ^{196}Po observed with the SAGE spectrometer at MARA.

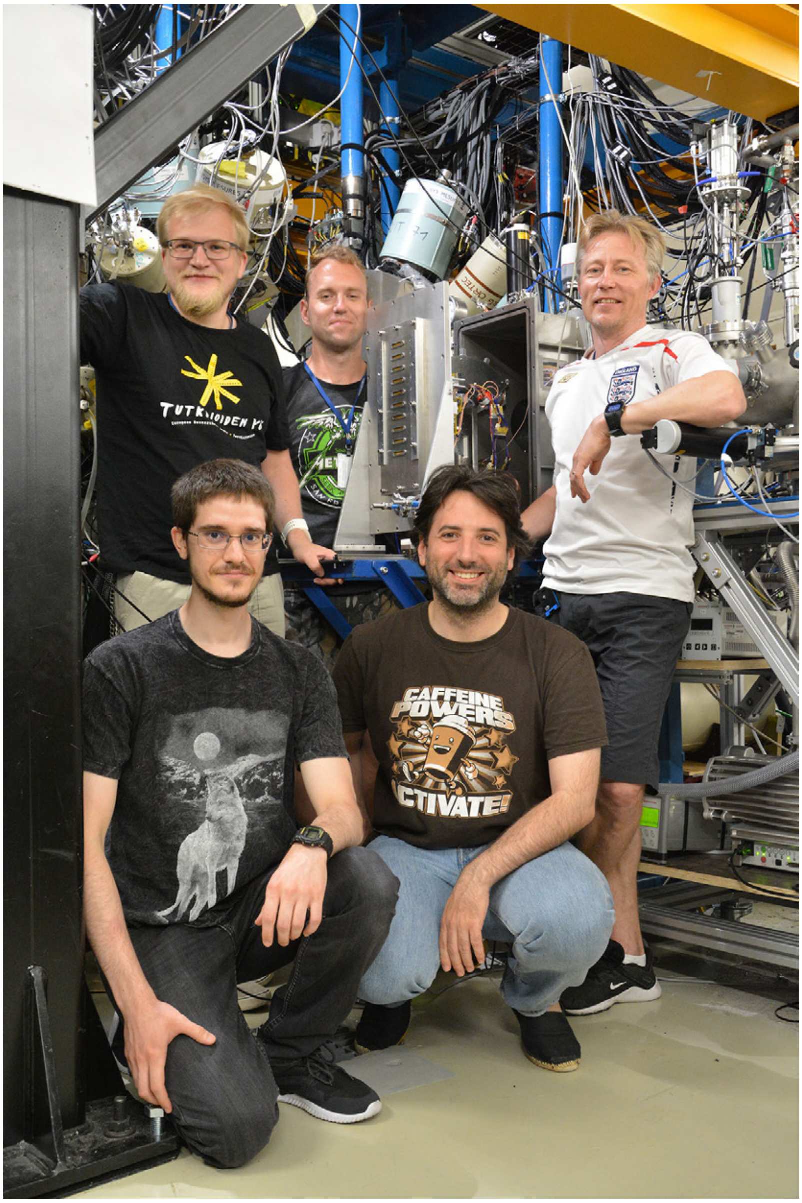
Another interesting use of MARA was demonstrated in the final experiment to be carried out at MARA in 2021, which was aimed at the investigation of the reaction dynamics of Multi-Nucleon Transfer and Quasi-Fission reactions. In this study, a beam of ^{65}Cu was used to impinge on ^{209}Bi and ^{238}U targets at (and slightly above) Coulomb barrier energies. The heavy, target-like recoils were guided to enter the MARA separator placed at angle of zero degrees. In addition to the JUROGAM 3 array at the target position, a CD-type silicon detector was placed at backward angles to collect the beam-like products. In this manner, it was possible to determine the full kinematics and the excitation pattern of the reaction products.

The end of 2021 also coincided with the end of the first campaign of JUROGAM 3 experiments at MARA, which began in 2019. The detectors of the JUROGAM 3 array are owned by the GAMMAPOOL consortium and are loaned to the Accelerator Laboratory on the basis of competitive scientific proposals which are submitted each year. The Clover detectors of JUROGAM 3 were transported to the ALTO facility in Orsay, France to be used in the array known as NuBALL. However, fifteen Phase 1 type detectors will remain at the Accelerator Laboratory and installed in a modified support structure, allowing in-beam studies to be continued. The Clover detectors are expected to return to the Accelerator Laboratory in 2023.

EXTERNAL RESEARCH

Members of the Nuclear Spectroscopy group continued their involvement in the construction of FAIR accelerator components and detectors together with the Helsinki Institute of Physics. The FAIR Phase-0 experimental programme continued with successful beamtimes in 2021. For example, the group participated in the study of level lifetimes in nuclei in the vicinity of ^{100}Sn using the fast-timing technique at the FRS.

The group also continued participation in experiments at ISOLDE, CERN. In addition, at the start of December, Janne Pakarinen left to ISOLDE to take up a temporary position for eight months as a Scientific Associate with the main focus on setting up the SPEDE spectrometer for a campaign at Miniball.



↑ Figure 3: (Left to Right) – Adrian Montes Plaza, Joonas Ojala, Andrew Briscoe, Andres Illana Sison and Janne Pakarinen following the successful installation of the SAGE spectrometer at MARA.

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EXOTIC NUCLEI AND BEAMS

Professors Ari Jokinen, Anu Kankainen and Iain Moore

Senior Researchers Tommi Eronen and Heikki Penttilä

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

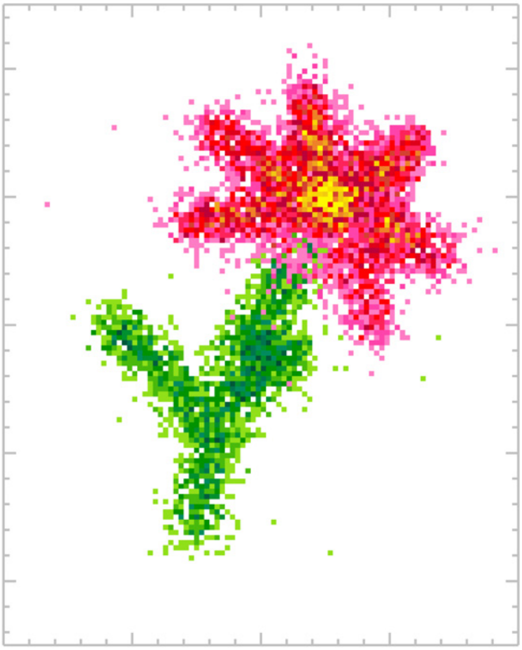
ON-GOING PROJECTS, RESEARCH ACTIVITIES AND NEWS

The members of the Exotic Nuclei and Beams research group are running several EU or Academy of Finland funded projects. Heikki Penttilä is the local coordinator of two EU EURATOM projects, a Joint Research Activity in SANDA (Supplying Accurate Nuclear Data for Energy and Non-energy Applications) and ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning), a transnational access project providing support for external user experiments at IGISOL. The European Research Council (ERC) Consolidator Grant project MAIDEN "Masses, Isomers and Decay studies for Elemental Nucleosynthesis" led by Anu Kankainen focuses on nuclear astrophysics. We are a beneficiary in the Marie Curie Innovative Training Network, LISA (Laser Ionization and Spectroscopy of Actinides), with one of the work packages (Exploring the limits of nuclear existence) led by our team. Our group is leading the development and exploitation of the first phase of MARA-LEB at JYFL-ACCLAB, with an ongoing Academy Project led by Iain Moore. In 2021, our group was awarded Academy Project funding in a consortium with theorist Markus Kortelainen, PANTHER, to advance our understanding of the actinide elements. In collaboration with University College London, a two-year Leverhulme research project grant was awarded to study nuclear magnetic octupole moments in caesium isotopes using the atom trap. In addition to the experimental programme at IGISOL, we contribute to the FAIR project. In 2021, members of our team participated remotely in Phase-0 experiments at FAIR/GSI. The experiments covered a broad spectrum of physics, including mass measurements and exploration of heavy nuclei close to the N=Z line and fission isomer studies.

Our group members received awards this year. Anu Kankainen was recognized with a GENCO membership award at the GSI, NUSTAR meeting. Ruben de Groote was also made a member and received the Young Scientist award for milestones in precision laser spectroscopy. The High Scientific Council of the European Nuclear Society selected Ilkka Pohjalainen to be one of five finalists for the ENS PhD award. Sonja Kujanpää was awarded the Finnish Physical Society's 2020 Young Physicist Prize for an excellent master's thesis in the field of physical sciences. Part of her work was published in Phys. Rev. A in 2021 [1].

DEVELOPMENTS

Despite an unfortunate accident connected with the helium purification system of IGISOL, we continued our developments in 2021. These included e.g. systematic studies of the phase-imaging ion cyclotron resonance (PI-ICR) technique at the JYFLTRAP double Penning trap. We discovered that the phase evolution of the radial motion of ions in a Penning trap during the application of radio-frequency fields leads to a systematic cyclotron frequency shift, when more than one ion species is present in the trap during the cyclotron frequency measurement [2]. This is an essential factor to be taken into account in the ongoing high-precision mass measurements of isomeric states at JYFLTRAP. The PI-ICR method has been employed in less conventional measurements, as highlighted in Fig. 1, illustrating the beauty of the technique.



↑ Figure 1. Using the JYFLTRAP Penning trap PI-ICR method to show our appreciation for the IGISOL team.

MORA

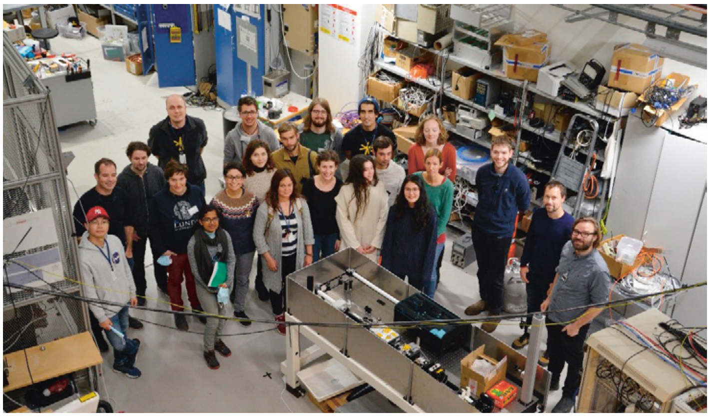
The Matter's Origin from RadioActivity experiment (MORA) will be searching for a signature of CP violation in the nuclear beta decay of radioactive nuclei produced at IGISOL. A large CP violation is actively searched for in high- and low-energy experiments to explain the matter–antimatter imbalance observed in the universe. In nuclear beta decay, the so-called *D* correlation violates time reversal, and via the CPT theorem, the CP symmetry. MORA aims at achieving a precision measurement of the *D* correlation in the decay of Mg-23 and Ca-39, reaching an unprecedented sensitivity to New Physics thanks to a unique combination of ion trapping and laser polarization techniques.

The MORA apparatus, indicated in Fig. 2, was installed in the IGISOL hall between November 2021 and January 2022. An intense period of offline activity followed, with successful trapping of Na-23 ions from a surface ion source just before the first on-line beam time in mid-February. During the beam time, beta activity from the decay of Mg-23 was recorded in the trap. The laser polarizing light was also available. Efforts are now concentrating on reducing RF noise on the recoil ion detectors and a large Na-23 isobaric contamination from the production target. A reduced contamination will permit an optimized use of the mini-buncher of the JYFL cooler, for an efficient capture of the Mg-23 ions into the trap of MORA. The on-line commissioning of the MORA apparatus will continue in May 2022.

↓ Figure 2. The team of French engineers, led by project leader Pierre Delahaye (front row, second from the left), recipient of a JYU visiting mobility grant, after the installation of the new ion trap, MORA.

The MORA experiment is supported by the French Agence Nationale de la Recherche (ANR) and Région Normandie. The MORA collaboration consists of GANIL, LPC Caen, IJCLab, JYFL-ACCLAB, KU Leuven, CERN-ISOLDE and IFIC, as partner laboratories. The MORA apparatus will eventually move back to GANIL once the DESIR installation is available, to pursue its scientific program from 2027 onwards. A workshop gathering the collaboration and international experts in the field of low-energy precision experiments will be held in May 2022 at JYFL: *https://indico.in2p3.fr/event/25986/*.

→ Figure 3. Marie Curie researchers are enjoying a group photograph at the IGISOL facility for their training week.



LISA

Our team organized a training week in October 2021 for the LISA Marie Curie Innovative Training Network. Approximately 20 Early-Stage Researchers from 10 different EU institutions spent a week in Jyväskylä, getting an introduction to modern ion manipulation and laser spectroscopic techniques used in radioactive ion beam research, applicable to fundamental nuclear structure research on the actinides. In addition to a series of lectures, practical activities were arranged in the Accelerator Laboratory, at IGISOL, MARA and the Pelletron facility. With the easing of COVID restrictions, the week was a resounding success and the first fully onsite training for the LISA students. There was an opportunity to experience a traditional sauna at the harbor area in support of a charity event hosted by the Finnish mental health institute which was taking place during the same week.

RESEARCH HIGHLIGHTS

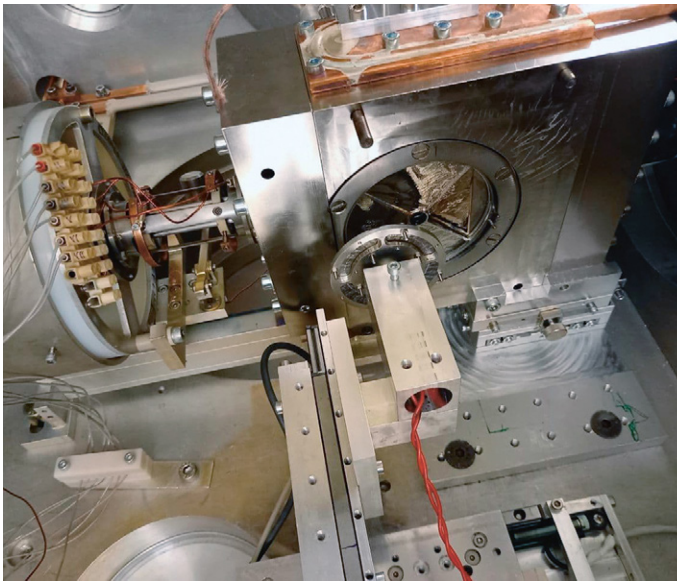
In the following, selected experimental and publication highlights from 2021 are summarized.

Novel techniques combine to explore the region below tin-100 for the first time

The region of the nuclear chart below tin-100, the heaviest bound isotope with the same number of protons (Z=50) and neutrons (N=50), has been of considerable interest in nuclear physics research. Here, atomic nuclei experience enhanced neutron-proton pairing, posing a fertile ground for testing the validity of theoretical predictions. Astrophysical processes taking place in x-ray bursts traverse nuclei in the region. Despite the extensive interest, technical difficulties in producing these nuclei have, until now, hindered the optical studies of these nuclei.

New configuration of the multinucleon-transfer ion guide commissioned

A new configuration of the multinucleon-transfer (MNT) ion guide was successfully commissioned in November 2021. In the new configuration, the primary beam is not stopped before the gas cell as in the previous version but is guided through the gas cell via a narrow tube and stopped in a graphite beam dump after it. The test was carried out using a 136Xe beam impinging into a rotatable 209Bi target. A better efficiency was achieved with the new configuration, most likely due to less primary beam scattering into the gas cell and the possibility to drive the target closer to the gas cell to allow a larger acceptance angle.



→ Figure 4. MNT gas cell with the beam tube going through the cell.

To probe these nuclei, we have implemented a combination of state-of-the-art technologies, including phase-imaging ion-cyclotron resonance (PI-ICR) Penning trap mass spectrometry, a hot cavity catcher ion source and resonance ionization spectroscopy. This project marks the first optical excursion below neutron number N=50 into the *N=Z* region below tin-100 with the measurement of the charge radii of silver-96 [3].

The state-of-the-art techniques were matched with a novel implementation of nuclear density functional theory, applied in collaboration with local theorist Markus Kortelainen. While all theoretical models provided a good reproduction of the measured charge radii in heavier silver isotopes, none of these models were able predict the sharp increase seen in silver-96. This result poses a challenge to present theoretical models and motivates new theoretical developments.

Since this pioneering experiment, we have measured the magnetic moment, masses, and charge radii of silver-95, with experiments targeting the mass of the isomeric states in silver-94 at the N=Z line soon.

Collinear laser spectroscopy highlights

Radioactive isotopes wedged between the magic numbers *N=Z*=20 and *N=Z*=28 have scarcely been studied with laser spectroscopy techniques, with challenges in the production of these isotopes at traditional ISOL facilities. The nuclear structure of this region is of particular interest to understand the evolution of collectivity between the magic nuclei bordering the proton and neutron f7/2 orbital. Nuclei along the *N=Z* line are also of interest and our investigation of the isomer shift in the self-conjugate Sc-42 has been published [4]. Technical developments have been made to access elements of vanadium, chromium, iron and cobalt. This includes an expansion of the spectral coverage of our laser systems and the optical detection system into the deep-UV range. A new light collection system was installed and equipped with photomultiplier tubes for the detection of photons between 200 nm and 300 nm.

Early in 2021, we performed laser spectroscopy on 48,49,51Cr, providing the first charge radius of a radioactive Cr isotope. In collaboration with colleagues from ISOLDE, we successfully measured the ground and isomeric states in *N=Z* 26Al. Offline, we investigated the hyperfine structure and experimental efficiency of vanadium on more than 10 transitions in the blue wavelength range. High-precision measurements of 59Co ions led to a 100-fold improvement on the precision of the hyperfine A factors and newly measurement B factors. This latter experiment successfully commissioned the new optical detection system and has been submitted for publication.

Lastly, as part of the LISA Marie Curie project, we have studied 10 different transitions in 234,235,238U, produced using an electric discharge source. The most efficient line will serve for the study of the second lowest-lying isomeric state in the nuclear chart, 235mU, produced through the alpha decay of 239Pu. We have acquired several sources of plutonium from the University of Mainz. These were characterized using Rutherford Backscattering Spectroscopy in collaboration with the Pelletron team, in August.

Beta decay Q-value measurements for neutrino studies

Laboratory experiments dedicated for measuring the mass of a neutrino are based either on beta decay or electron capture. So far only ground-state-to-ground-state decays, such as ^{3}H and ^{163}Ho, have been utilized in neutrino mass measurements. A prerequisite for measuring neutrino mass via decay kinematics is a small decay energy (Q value). Smaller the Q value, more decay events land near the endpoint of the decay spectrum, where the mass of a neutrino manifests itself. We have mapped Q values of several decay candidates using the JYFLTRAP Penning trap mass spectrometer. The candidates potentially have a decay branch to an excited state in the daughter nucleus so that the beta decay or electron capture proceeds with a minimal Q-value.

In 2021, the analysis for the electron capture in ^{159}Dy was completed. Based on the results, its electron capture spectrum was modeled with nuclear and atomic calculations. The Q-value measurement revealed a decay channel within a sweet energy range. Theory collaborators, including local J. Suhonen's group, pursued to model the decay. Efforts revealed the electron capture in ^{159}Dy to be about ten times more sensitive to electron-neutrino mass than the ground-state-to-ground state electron capture of ^{163}Ho, which is currently utilized in neutrino-mass measurements. The results were published in Physical Review Letters, see reference [5].

Selected publications

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[2] D.A. Nesterenko et al., Eur. Phys. J. A 57, 302 (2021). [Open Access] *https://doi.org/10.1140/epja/s10050-021-00608-3*

[3] M. Reponen, R.P. de Groote et al., Nature. Comm. 12, 4596 (2021). [Open Access] *https://doi.org/10.1038/s41467-021-24888-x*

[4] A. Koszorus et al., Phys. Lett. B 819, 136439 (2021). [Open Access] *https://doi.org/10.1016/j.physletb.2021.136439*

[5] Z. Ge et al., Phys. Rev. Lett. 127, 272301 (2021). [Open Access] *https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.127.272301*

INSTRUMENTS AND METHODS
IN NUCLEAR, PARTICLE, AND ASTROPARTICLE PHYSICS

Senior Researcher Wladyslaw H. Trzaska

One of the most exciting aspects of experimental physics is doing what nobody has done before. Developing new instruments and methods is an integral part of that process. Over the past decades, the HENDES group's activities expanded from low-energy nuclear physics to relativistic heavy-ion collisions, neutrino physics, ultra-relativistic cosmic rays, and indirect Dark Matter searches. In addition to various spectrometers and devices for 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 Underground Physics is given in the Neutrino and Astroparticle Physics. This section concentrates on Nuclear Reaction studies carried out at the K130 cyclotron and other European facilities.

https://www.jyu.fi/hendes

We are sad to inform you that in a short span of 12 months, we have lost three exceptional friends and colleagues who were instrumental in shaping Nuclear Reaction (NR) studies at the Accelerator Lab. Valery Rubchenya initiated fusion-fission research at JYFL and made significant contributions to HENDES and IGISOL research groups. He also served as our PAC member. Valery was active to the very end. Unfortunately, he died just one day before he was scheduled to talk at the prestigious NUCLEON 2020 conference.

Neutron measurements dominated the early fusion-fission experiments in Jyväskylä. In addition to the Position Sensitive Neutron Detectors designed in the Radium Institute in St. Petersburg, we collaborated and used neutron detectors provided by the DEMON group, led by Francis Hanappe. Francis also served as the opponent at our group's first PhD defence.

While Valery's and Francis' contributions peaked during the first decade of the HENDES group, the importance and activity of Alexey Ogloblin's team never faded over the past three decades. In addition,

← Figure 1. Valery, Alexey and Francis, photographed by W.H. Trzaska, during the EXON 2016 conference in Kazan.

Alexey was a member of the first PAC and organised the construction and delivery of our Large Scattering Chamber (LSC) – the workhorse of NR research at JYFL.

The persistent COVID-19 travel restrictions forced us to postpone all approved NR experiments for one more year. We have used this extended break for a major reconstruction and modernisation of the LSC cavern. We have also continued data analysis. One of the interesting results is the stabilising role of proton numbers at Z ≈ 36, 38, Z ≈ 45, 46 and Z = 28/50 in asymmetric fission of excited preactinide nuclei. In the total kinetic energy distributions of $^{180,190}Hg$ fission fragments measured by us, the high (≈ 145 MeV) and low (≈ 128 MeV) energy components correspond to the fragments with proton numbers near Z ≈ 46 and Z ≈ 36. Our results on the studied properties of asymmetric fission of $^{180,190}Hg$ and $^{184,192,202}Pb$ nuclei point to the existence of a well-deformed proton shell at Z ≈ 36 and less deformed proton shell at Z ≈ 46.

Another interesting result is the evidence of quasifission in the ^{180}Hg composite system formed in the ^{68}Zn + ^{112}Sn reaction. For this reaction, the Coulomb parameter Z_1Z_2 is equal to 1500, which is close to the threshold value for the appearance of the quasifission process. We have observed that mass-energy fragment distributions differ significantly from the ^{36}Ar + ^{144}Sm reaction leading to the same composite system at similar excitation energies. We explain the difference by an unexpectedly large contribution (more than 70%) of quasifission in the case of the ^{68}Zn + ^{112}Sn reaction.

We have also analysed the $^{11}B(^3He,d)^{12}C$ reaction measured with 25 MeV ^3He beam. We have determined differential cross sections for the 13.35 MeV state and the states with excitation energy around 20 MeV in ^{12}C. Based on our DWBA-based analysis, we propose a tentative assignment, 4−, for the state at 13.35 MeV. For the state at 20.98 MeV, we assign spin-parity 3− and the isospin T =0. Our model description of the broad state at 21.6 MeV is consistent with the previous assignments of isospin T = 0 and spin-parity of 2+ or 3−. The possible spin-parity of the excited 22.4 MeV state is either 6+ or 5−. For a definitive answer, a more extensive data sample is needed.

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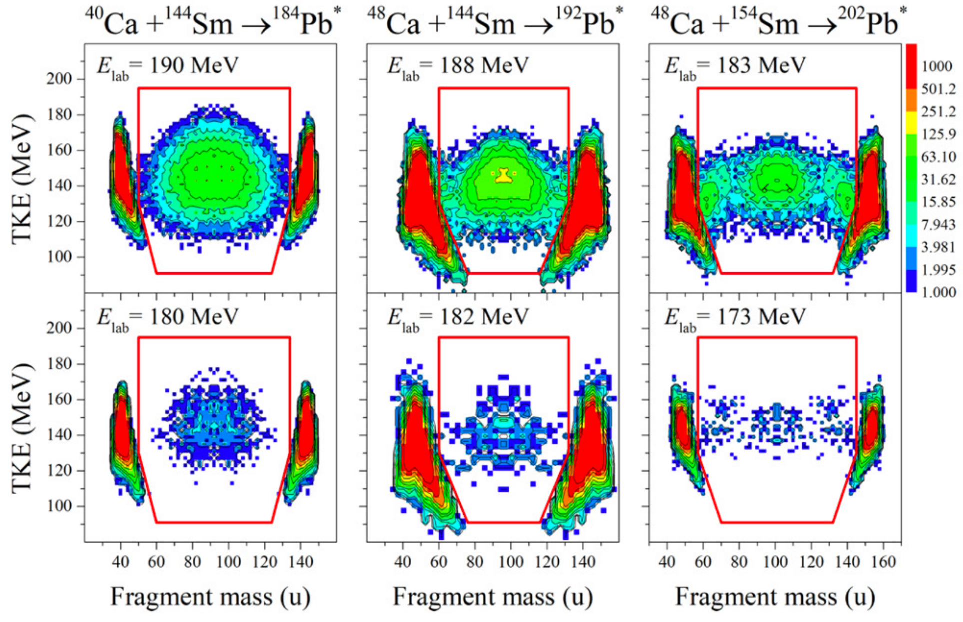


↑ Figure 2. Binary fragment mass-energy distributions from the ^{40}Ca + ^{144}Sm and ^{48}Ca + $^{144,154}Sm$ reactions.

NUCLEAR STRUCTURE AND NUCLEAR PROCESSES

Professor Jouni Suhonen

The nuclear-theory group at JYFL applies various nuclear-structure models to topics of current interest in weak-interaction physics. The topics pursued include neutrino-nucleus interactions at solar and supernova energies, rare weak decays like forbidden beta decays and double beta decays, nuclear muon capture, WIMP-nucleus scattering for direct dark-matter detection and reactor neutrinos. The group is a theory partner in many large international experimental collaborations and research laboratories. It pursues also intense collaboration with the local Global properties of nuclei and JYFLTRAP groups, as well as some external theory partners.

www.jyu.fi/physics/accelerator/nuclear-structure-and-nuclear-processes

TOWARDS THE SOLUTION OF THE REACTOR-FLUX ANOMALIES

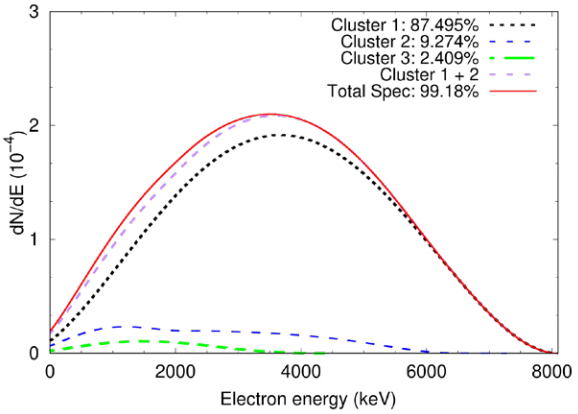
By now the neutrino-oscillation experiments have produced accurate information on the mixing and relative masses of neutrinos. The related analyses have usually been carried out in the three-flavor framework which, however, has been challenged by the results of the RENO, Double Chooz and Daya Bay short-baseline reactor experiments [1]. These experiments could measure the antineutrino flux created by the beta decays of the reactor fission products. By comparing the measured flux with that derived from the nuclear-decay databases a deficit in the measured flux was recorded. This deficit was coined the “reactor antineutrino anomaly” (RAA) and was subsequently interpreted as being caused by oscillations to a fourth neutrino flavor, the sterile neutrino, which does not interact with ordinary matter. Such neutrinos are currently under a vigorous experimental search. Also, an unexpected “bump”, an extra increase in the measured number of antineutrinos between 4 and 7 MeV of antineutrino energy, was registered. At the time of detection, no hint of the origin of this bump could be found.

The nuclear data bases used in building the cumulative antineutrino flux from the data on half-lives and branching ratios of beta transitions in the individual fission products suffer from several inherent flaws: Not nearly all the relevant beta transitions have been measured and the existing data is prone to systematic errors owing to the limited efficiency of the germanium detectors used in the beta-decay measurements. In addition, the involved beta-minus decays have a continuous electron spectrum up to a maximum electron energy, the so-called beta endpoint. The corresponding electron spectral shapes are known only for certain simple special cases where the spectral shape is universal, independent of the nuclear-structure details. For the more complicated spectral shapes, which depend on the wave functions of the initial and final nuclear states, there are practically no data. Hence, the reactor antineutrino spectra had to be constructed starting from electron spectral shapes approximated as universal.

In [2], for the first time, it could be shown quantitatively that the approximation of simple electron spectral shapes could lead to the RAA and spectral bump. In this study the complex spectral shapes of the beta transitions, responsible for the bulk of the reactor antineutrino flux, were constructed by computing the involved nuclear wave functions using the nuclear shell model (NSM) with up-to-date nuclear Hamiltonians. The related antineutrino flux was coined the HKSS (from the initials of the authors) flux model in [3].

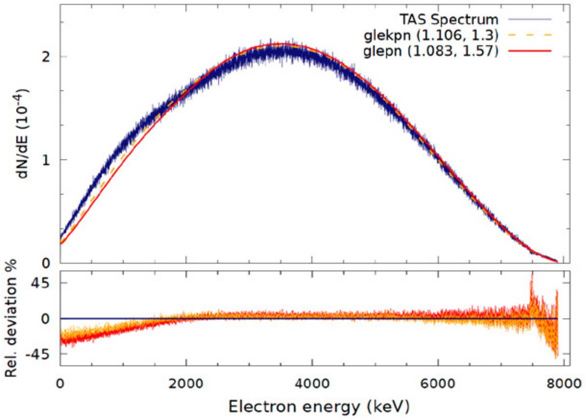
The RAA and the bump anomaly have been among us for roughly a decade now and new ideas to solve them are called for. One possible strategy consists of computations of the total electron spectra of all those nuclei which basically produce the final measured reactor flux. Summing up all these computed spectra leads to a full electron spectrum which can be converted to an antineutrino spectrum and compared with the measured one. This would be an extremely challenging task if no experimental support were available. Fortunately, recently there are available beta branching-ratio data obtained via the total absorption gamma-ray spectroscopy (TAGS). In particular, there are data on the beta branchings of Rb-92, one of the major contributors to the reactor antineutrino flux. This data was measured at the JYFL Accelerator Laboratory some years ago [4].

We set out to determine the total electron spectral shape of Rb-92 based on the TAGS-measured branchings to a plethora of final states in Sr-92 within the challengingly high beta-decay window of some 8 MeV [5]. We opted for a step-wise procedure where clusters of final states were formed to increase the stability of the analyses involved. Cluster 1 consisted of the transition to the ground state of Sr-92 and cluster 2 contained transitions to 6 low-lying excited states. The effective values of the weak axial-vector coupling (see [6] for its relation to a measured electron spectral shape) and axial charge [1] were determined by using the TAGS data pertaining to clusters 1 and 2. Cluster 3 contained the rest of the transitions, with branchings based partly on TAGS, partly on the NSM calculations. All the related electron spectral shapes, except the universal ones, were determined by using the NSM-computed wave functions. The accumulation of the full electron spectral shape is shown in figure 1.



↑ Figure 1. The computed total (99.18% for computational reasons) electron spectral shape of the Rb-92 beta decay and its decomposition into spectral shapes corresponding to transition clusters 1-3 (see the text).

The computed total spectral shape is compared with the one based on the TAGS data (TAS spectrum) in figure 2. The TAS spectrum is constructed from the measured TAGS branchings by making the approximation of treating all the spectral shapes as universal. The fuzziness of the TAS curve stems from the uncertainties in the TAGS-measured branchings. From the figure one notices that for low electron (kinetic) energies, below 2 MeV, the NSM-based curve predicts a deficit in the number of electrons thus converting to a deficit of antineutrinos at energies above 6 MeV (the beta-endpoint energy is about 8 MeV). In the region 2-4 MeV there is a slight increase in the NSM-predicted number of electrons, converting to an increase in the number of antineutrinos in the "bump region" 4-6 MeV. This shows clearly that a proper treatment of the complex electron spectral shapes is a potential solution to the long-standing issue of the reactor flux anomalies.



↑ Figure 2. Upper panel: Comparison of the TAGS-based simulated spectrum (TAS, universal spectral shapes assumed for all beta transitions) with the NSM-based one. Lower panel: Relative deviation in percent of the NSM-based curve from the simulated TAS curve.

Selected publications

[1] H. Ejiri, J. Suhonen and K. Zuber, Physics Reports 797, 1-102 (2019).

[2] L. Hayen, J. Kostensalo, N. Severijns and J. Suhonen, Physical Review C 99, 031301(R) (2019), ibid. C 100, 054323 (2019).

[3] J. M. Berryman and P. Huber, Phys. Rev. D 101 (2020) 015008.

[4] A.-A. Zakari-Issoufou et al., Physical Review Letters 115 (2015) 102503.

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GLOBAL PROPERTIES OF NUCLEI

Associate Professor Markus Kortelainen

Our group develops and applies nuclear structure models, focusing mainly on 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, throughout the nuclear chart. We also collaborate with the experimental nuclear physics groups at the JYFL accelerator laboratory and with the local nuclear structure and nuclear processes theory group.

https://www.jyu.fi/science/en/physics/research/nuclear-and-accelerator-based-physics/fidipro-project

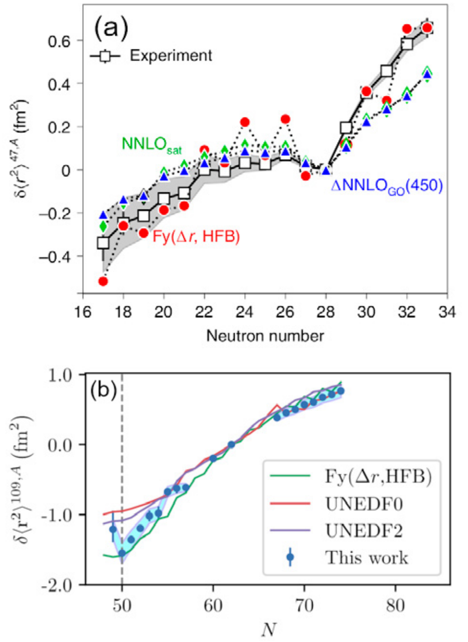
NUCLEAR CHARGE RADII WITH FAYANS ENERGY DENSITY FUNCTIONAL

The nuclear charge radii can provide abundant information about the underlying nuclear structure and interactions. The evolution and local variation of the charge radius poses a challenge to the nuclear theory, which has not yet been sufficiently solved. In recent works, we used Fayans energy density functional to interpret measured charge radii.

In the first work [1], neutron rich potassium isotopes were measured at ISOLDE, CERN. For theoretical calculations, two different approaches were used: Nuclear density functional theory and coupled cluster theory. While both theoretical approaches reproduced the general experimental trend of charge radius isotopic shifts, some shortcomings were noted.

The second work [2] was done in collaboration with the local exotic nuclei and beams research group. In this work, silver isotopes were measured at the JYFL accelerator laboratory, resulting in a strikingly large observed charge radius in proton rich silver-96 isotope. While all used theoretical models, based on nuclear density functional theory, could provide a good reproduction of the measured charge radii in heavier silver isotopes, none of them were able predict the sharp increase seen in silver-96 when crossing the N=50 shell closure.

The data on charge radii from both potassium and silver isotopic chains (see Fig. 1) poses a challenge to present theoretical models and motivates to improve present nuclear structure models.



↑ Figure 1. Isotopic shifts of charge radius in K isotopic chain (a) and Ag isotopic chain (b). Adjusted from [1] (a) and [2] (b).

PANTHER CONSORTIUM

In 2021 our research group was awarded with a project grant from Academy of Finland. The PANTHER consortium consists of one theoretical and one experimental research project. The goal of this consortium is to advance knowledge on the actinide nuclei, both experimentally and theoretically.

[1] Á. Koszorús, et. al., Nature Phys. 17, 439 (2021).

[2] M. Reponen, et. al., Nature Comm. 12, 4596 (2021).

RADIATION EFFECTS

Staff Scientist Heikki Kettunen
Senior Researcher Arto Javanainen

We specialize 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 2020 and will continue until the end of 2022.

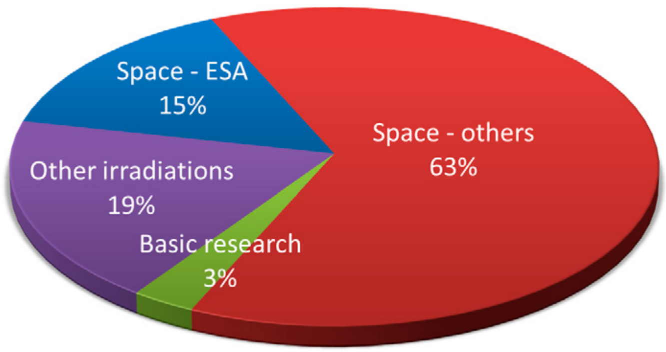
www.jyu.fi/accelerator/radef

Four different heavy ion cocktails, proton, X-ray, and electron beams are available for irradiation tests at RADEF. The mostly used beam is 16.3 MeV/n heavy ion cocktail. The selection of available ions in the cocktails are developed continuously with the Ion Source group. On 2021, Ag- and B-beams were developed and tested couples of times, but some development is still needed before regular use.

2021 was still a difficult year for everyone, due to the COVID-19 pandemic and travel restrictions. However, RADEF was able to offer beam time also to foreign visitors throughout the year. Some of the experiments were done remotely, but in major part, visitors came on-site for their experiments. Many thanks to our customers who were willing to visit RADEF and comply with all the quarantine and COVID-19 tests requirements as well as all the other safety guidelines. Let's hope that the coming years are easier on that scene.

RADEF used 1488 hours of K130-accelerator beam time in 57 campaigns with 21 different companies, institutes and universities. This corresponds to 24 % of the K130 beam time hours in 2021. The distribution of this beam time between different users shown in Fig.1. The total revenue of RADEF (commercial, EU and ESA projects) in 2021 was about 1.2 M€.

In addition to K-130 beam time, the Clinac electron accelerator was actively used for PhD thesis and other research studies.



↑ Figure 1. Distribution of RADEF beam hours for different activities (SpaceESA = ESA beam hours, Spaceothers = beam hours for space companies).

ESA PROJECTS

Estimation of proton induced Single Event Effect rates in very deep submicron technologies

In order to improve standard methods to characterize proton SEE sensitivity by direct ionization, and then estimate the SEE rates in orbit, in 2020 ESA granted funding for a 2-year project to Alter Technologies Ltd (France) and RADEF to study low energy proton effects in modern memory technologies. In addition to providing proton and ion beam for this study, RADEF has performed simulations and numerical studies to complement the experimental results. The objective is to build models and calculation methods to estimate soft error rates in space that will take into account contributions of low and high energy protons, but also heavy ions present in radiation environments.

Radiation Characterisation of EEE components for ESA space applications

Commercial Off The Shelf (COTS) electronics have become increasingly popular for space applications in the recent years due to their advantages in price and performance over radiation hardened technologies. The radiation sensitivity of COTS parts can vary and before using them in radiation environments (like space) they need to be tested using radiation sources. RADEF is part of ESA-funded project with RUAG Space Finland in order to perform radiation effects tests on various electronics devices that are candidates for ESA space missions.

EU PROJECTS

RADNEXT

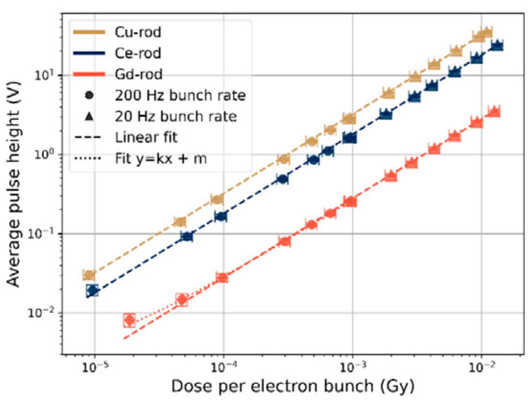
EU Horizon-2020 project called "RADiation facility Network for the EXploration of effects for indusTry and research" (RADNEXT) was granted funding in 2020. This 4-year and 5Meur project is coordinated by CERN with 31 participants in 12 countries. The implementation of the project started in the spring of 2021. The primary objective is to create a network of facilities and related irradiation methodology for responding to the emerging needs of electronics component and system irradiation for New Space, automotive, IoT, nuclear dismantling and civil applications, medical and accelerator applications; as well as combining different irradiation and simulation techniques for optimizing the radiation hardness assurance for systems, focusing on the related risk assessment. RADEF is providing Transnational Access for the users for radiation effects testing through this project.

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 Horizon 2020 project (GA#721624) was granted total of 3.9 M€.

ELECTRON-BEAM DOSIMETRY WITH OPTICAL FIBRES

At RADEF, optical fibre-based dosimetry systems have been tested in collaboration with the University Jean-Monnet in Saint-Etienne, France. Silica glass rods doped with ions making them radioluminescent are used as radiation sensors, and the radiation-induced luminescence in the rods can be transported to a readout system based on e.g. photomultiplier tubes (PMT). The luminescence response against the pulsed electron beam produced by the Clinac at RADEF is, as can be seen in Figure 2, linear against the electron bunch dose, with doses varying over a wide range. Results from samples doped with Ce^{3+}, Cu^{+}, and Gd^{3+}-ions, and for two different electron bunch rates are shown in the figure. The Gd-rod sample produce less light than the other samples, and lose linearity at low dose-levels in the used configuration. The tested silica glass rods have a small volume, with a length of 1 cm and a diameter of 1 mm, and they are inert and stable which allows use in varying applications, such as in chemotherapy. The different dopant ions have different luminescent properties in terms of emission spectrum and decay time, which makes different dopants suitable for different applications. [1]



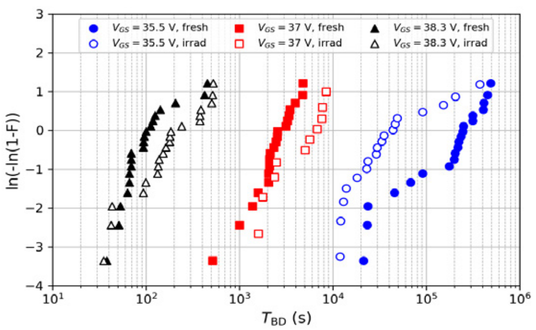
↑ Figure 2. Radioluminescence response of doped silica glass rods with different dopants at varying electron bunch rates. Output voltage pulses from a PMT as a function of electron bunch dose.

ELECTRON RADIATION IMPACT ON THE LONG-TERM RELIABILITY OF SILICON CARBIDE POWER MOSFETS

Silicon carbide (SiC) has gained interest in critical power electronics applications due to its superior material properties over silicon. SiC has high critical electric field, high thermal conductivity and high melting point, which are favourable properties where high power density is needed. However, a high sensitivity to destructive failures induced by the energetic particle radiation limits the application of SiC power devices in space environment.

During their operation in the space environment, on top of the radiative stress, those devices are exposed to electrical stress, and as for any system, reliable operation of power electronics devices is needed for full desired lifetime of the system. Therefore, on top of the sensitivity to catastrophic failures, it is important to assess if the operation in radiation environments causes a reduction in the lifetime of these devices.

Accelerated wear-out and electron radiation tests were performed by using the RADEF linear electron accelerator. The 20 MeV electron beam induces damage in the SiC power device material resulting in reduction of time-to-breakdown for irradiated devices in accelerated lifetime test (Figure 3).



↑ Figure 3. Time-to-breakdown distributions of non-irradiated and irradiated devices.

Selected publications

[1] D. Söderström et al., “Radioluminescence Response of Ce-, Cu-, and Gd-Doped Silica Glasses for Dosimetry of Pulsed Electron Beams” Sensors 2021, 21(22), 7523.

ION SOURCES

Senior Lecturer Hannu Koivisto
Senior Researcher Ville Toivanen

The ion source group develops ion sources and ion beams for the users of the JYFL Accelerator Laboratory. The group also conducts plasma research and development of plasma and ion beam diagnostics. The main objective of the group is to improve highly charged ion beams for the international user community in terms of beam variety and intensity without compromising the beam quality and stability.

www.jyu.fi/science/en/physics/research/nuclear-and-accelerator-based-physics/ion-sources

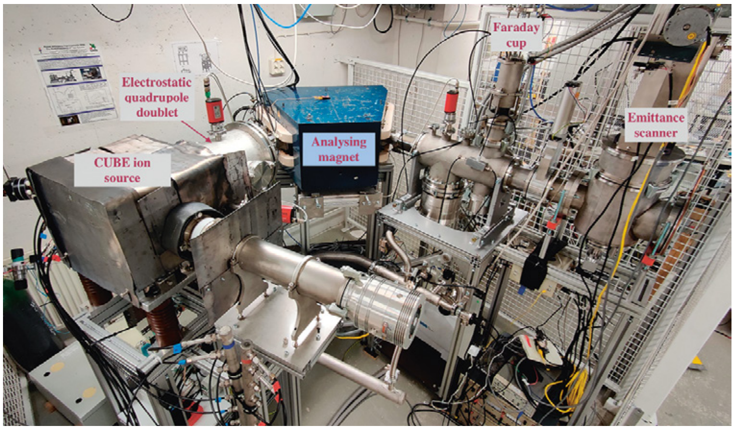
STATUS OF THE CUBE PROTOTYPE

The Academy of Finland granted a four-year funding (1.9.2018–31.8.2022) for the project: *"The effect of a magnetic field configuration on the performance of minimum-B ECR ion sources"*. As a part of the project an innovative ECR ion source prototype CUBE has been designed and realized with a magnetic field structure that differs significantly from the conventional ECRIS designs. The main objective of the project is to investigate the capability of CUBE to produce highly charged ion beams (with performance target of 1 µA of Ar^{10+}), compare the stability of the magnetically confined plasma with conventional ECR ion sources and study beam formation from ECR-heated plasma with an extraction system based on a slit aperture and electrostatic quadrupoles. Figure 1 shows the status of the CUBE ion source setup at the end of 2021.

The first plasma was produced with CUBE in summer 2021. The first ion beams were produced in November 2021 and during November and December ion beams of multiply charged argon, helium and krypton were successfully extracted from CUBE. In this commissioning phase the beams were extracted through a round plasma electrode aperture with 8 mm diameter. The intensities of the extracted ion beams were substantially limited by problems related to the high-voltage insulation of the source. Regardless of this problem and the constraints it caused, the CUBE prototype was able to produce 5 µA and 0.23 µA of Ar^{8+} and Ar^{10+} ion beams, respectively. The high voltage capabilities have been recently improved and the system has been tested up to its designed operating value of 10 kV without any issues. As the next step the extracted beam properties will be systematically characterized with the round extraction aperture and the performance of the source will be defined with the nominal extraction voltage of 10 kV to set a baseline for the following slit extraction studies. The slit extraction, which is the intended scheme to optimize the beam formation from the CUBE magnetic structure, is expected to further improve the CUBE beam performance. We are confident that the original research program will be completed successfully, and the prototype performance targets will be met before the end of the project.

PLASMA RESEARCH

The other part of the Academy funded project focuses on the kinetic plasma instabilities which strongly limit the production of highly charged ion beams. In a recent research campaign, the relationship between the instability repetition rate and the strength of the instability events was studied with a sophisticated multi-diagnostic



← Figure 1. The CUBE setup, which includes the CUBE ion source, electrostatic quadrupole focusing designed for the slit extraction, analysing magnet for q/m separation, Faraday cup for measuring the charge state distribution and the emittance scanner to study the quality of the extracted ion beams.

system combining detection of microwave, x-ray and particle emissions with high temporal resolution (16 ns). A comprehensive overview of these and other diagnostic techniques to study ECR-heated plasma instabilities is presented in a recent invited review article by V. Toivanen et al. [2].

The kinetic plasma instability is driven by the anisotropy in the electron energy distribution caused by the excessive contribution of high energy electrons. During an instability event this excessive energy is dissipated as a result of electron-electromagnetic plasma wave interaction where high-energy electrons will transfer their kinetic energy to the plasma wave and, as a result, lose their magnetic confinement. One of the most significant discoveries of the recent campaign was that the plasma instabilities are often grouped into bursts of microwaves and electrons from the magnetic confinement. Figure 2 illustrates, as an example, the grouping of instabilities. Each instability event can consist of 1 to 9 separate instability bursts in quick succession, separated by a longer recovery/accumulation time (see Fig. 2). The grouping implies that there is a fundamental limit for the stored energy dissipated by a single instability burst. It was also found that the quiescent time between the instability events depends on the total energy dissipated during the event. Increasing the plasma energy content by adjusting the plasma heating parameters, in particular the magnetic confinement, makes the instabilities more chaotic in time domain. A recently published study by the group also suggests that the instability transition can be affected by local modification of the weakest magnetic mirror of the plasma confinement [3]. This would allow to control of the electron losses and therefore affect the electron energy distribution function and the occurrence of kinetic instabilities.

Ion beam formation has been another important focus of the group's activities in 2021. The aim of these studies is to better understand the role of Child-Langmuir law in systems where the beam is extracted from a plasma volume [4]. In addition, the capabilities of POSSU spectrometer, developed to study the visible light emitted by plasma, have been upgraded to make time resolved ion population studies possible. The upgraded time resolved visible light diagnostics combined with the highly-charged plasma is a unique combination that will be used in the future to reveal new information, for example, about the influence of plasma instabilities and other plasma transients on the confinement properties and the step-wise ionization process of highly charged ions [5]. A collaboration with LPSC, France, also focuses to study the properties of ECR-heated plasmas by combining experiments and numerical plasma modelling. In 2021 the project successfully provided new insight into ionization, charge exchange and ion confinement times [6].

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[1] B. Bhaskar, H. Koivisto, O. Tarvainen, T. Thuillier and V. Toivanen, Quasi-periodical kinetic instabilities in minimum-B confined plasma, AIP Advances 12, (2022), p. 015223.

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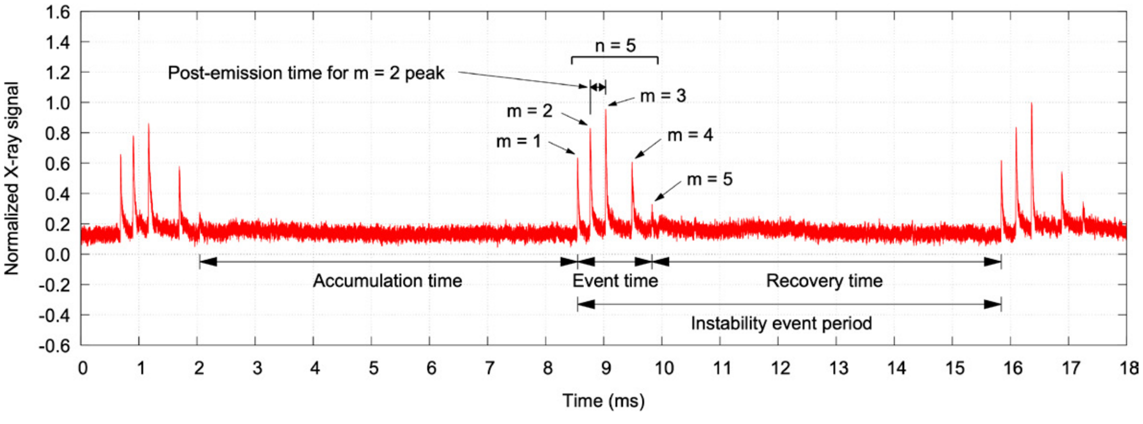


↑ Figure 2. An example of grouped plasma instabilities. The determination of the burst numbers *m*, event (mode) number *n* and the accumulation time, event time, recovery time and instability event period are also presented. The instability event is defined to be the group of bursts with *m* = 1...5, i.e. *n* = 5 in the example. The time from one burst to the next one within an event is denoted as post-emission time, presented here as an example for the m = 2 burst.

ACCELERATOR BASED MATERIALS PHYSICS

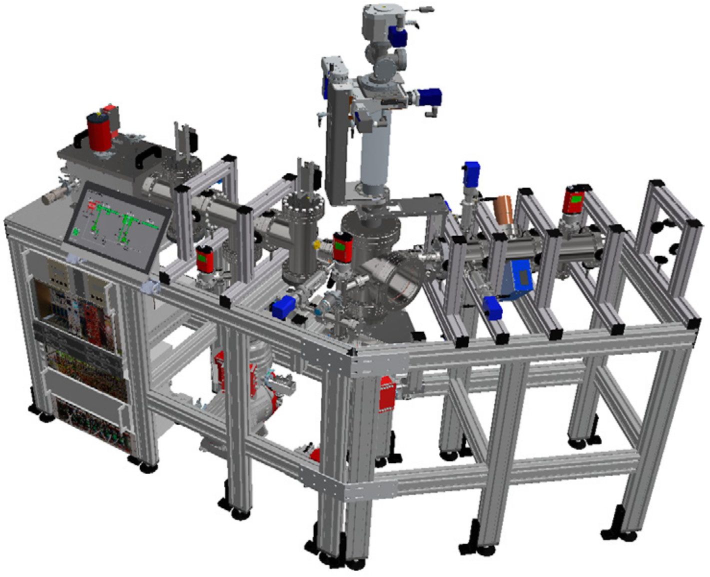
Professor Timo Sajavaara
Academy Research Fellow Mikko Laitinen
Senior Lecturer Kai Arstila
Postdoctoral researcher Jaakko Julin

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) applications 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 the Nanoscience Center (NSC) clean room the group is an active user of a helium ion microscope (HIM) and has a couple of versatile atomic layer deposition (ALD) tools. The group is an active link between the two research infrastructures, Accelerator Laboratory and Nanoscience Center.

www.jyu.fi/physics/accelerator/abasedmat

COMMERCIAL TOF-ERDA DELIVERY

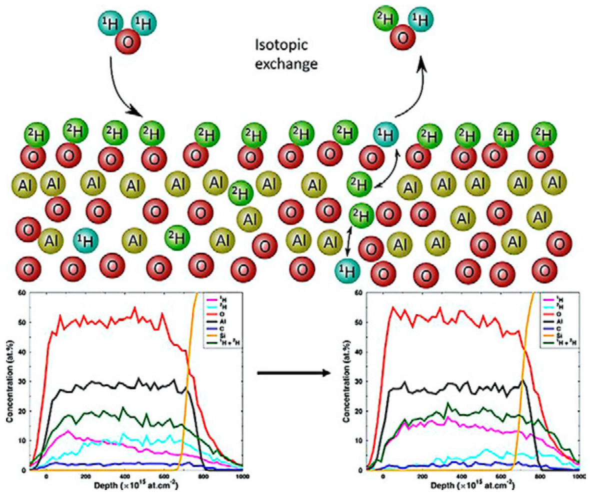
The earlier track record of our ToF-ERDA research had resulted 2-3 commercial deliveries of timing detectors and gas ionization detectors to other institutes, like 2011 for the University of Montreal and 2013–2015 to the Imec in Belgium. During 2021 we had an opportunity to not only upgrade our existing state-of-the art detectors but to construct a complete ToF-ERDA spectrometer, together with beam line end-station, for the University of Surrey, see Figure 1. Even though the actual on-site installation slipped to the beginning of 2022, we managed to build the system with highest ever recorded hydrogen detection efficiency, exceeding our own setup's performance with up to 25–30%. What was also improved over our existing setup were much better sample handling for up to 100 mm wafers, thick samples, the possibility to do easier stopping force measurements, and the full automatization of the measurement and DAQ system. This type of commercial activity opens up new possibilities also for basic research. From the funding perspective, the surplus obtained from such commercial projects can now be used to boost the research funding for those personnel whose time was used for this type of wider societal activities.



↑ Figure 1. ToF-ERDA spectrometer, including from right to left: beam line with beam profile monitor and motorized slits, measurement chamber with 4 axis sample manipulator, time-of-flight detectors and gas ionization chamber, with the included DAQ automation and vacuum and motion control.

ATOMIC LAYER DEPOSITION ACTIVITIES

ALD activity remained strong for our research group. Isotopic enriched precursors were used to deposit Al_2O_3 and ZnO films [1-2]. Both heavy water and enriched ^{18}O were used to study the hydrogen and oxygen exchange reactions in the deposition films [1]. It was surprising that even at room temperature the deuterium, as an impurity in the Al_2O_3 film, was replaced by hydrogen ^{1}H, while the total concentration of the hydrogen impurity did not change (see Fig. 2). On the other hand, the oxygen exchange did practically occur in these films potentially reflecting the permeability of the deposited material. During the 2021 the ALD related collaboration with JAMK (University of Applied Sciences) also continued. Our group loaned the Beneq TFS 500 unit to the JAMK, in addition to the earlier donated WCS 500 unit, which is now fully capable for roll-to-roll pilot production. The iADDVA project (Adding Value by Creative Industry Platform) had an EU regional funds funding decision with the total volume of 864 k€ from which about 150 k€ comes for the physics during two years. The project is coordinated by JAMK and other participants are JYU (physics+IT) and City of Jyväskylä.



↑ Figure 2. Depth profile of the ALD film grown by heavy water ($^{2}H^{16}O$) and trimethylaluminium (TMA) precursors. The deuterium ^{2}H was proven to be exchanged to ^{1}H if the films were aged even in the room temperature and atmosphere. Reprinted with permission from Elsevier. [2]

ION-BEAM ANALYSIS

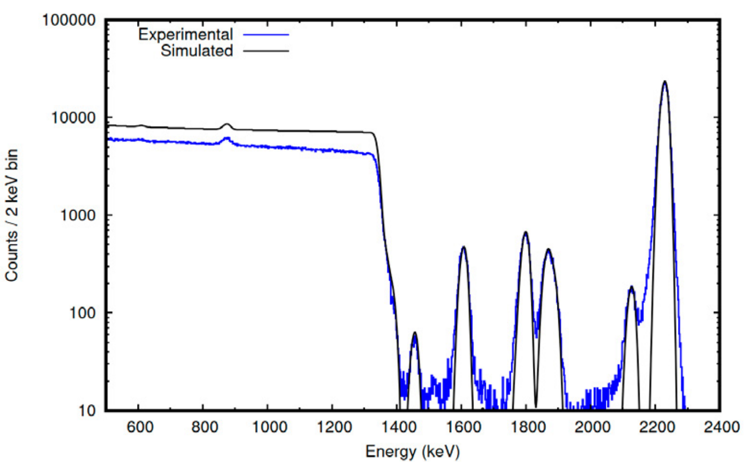
The ToF-ERD Analysis software Potku development has now been continued without a stop for a couple of years. The actual coding is mainly done by physics and IT students, and with their help the next versions are rolling out a few times a year. During 2021 the first Potku user-webinar was held and 42 participants took part from about 10 different laboratories around the world.

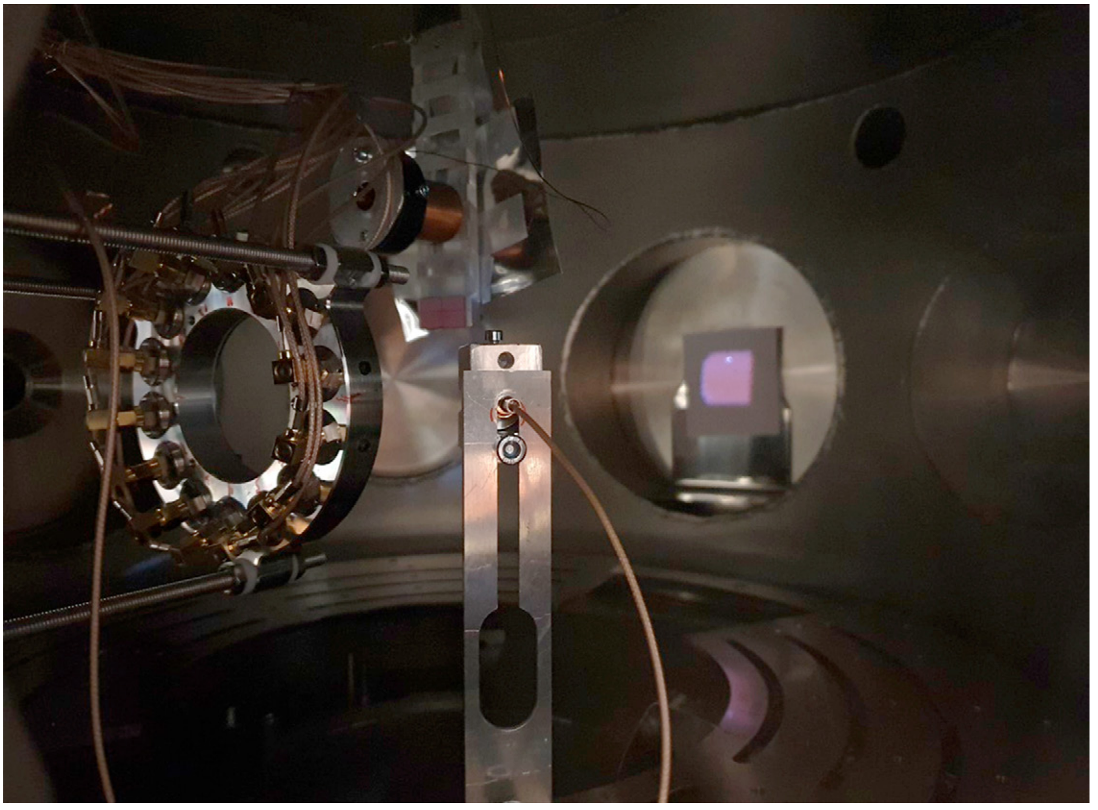
During 2021 our ion beam analysis laboratory saw its first ^{239}Pu and ^{240}Pu samples being measured. Extra care was taken also to prevent the measurement chamber contamination from the samples, which were measured by us for the IGISOL collaborators, see figure 3. The outcome of these RBS measurements helped to improve the deposition process of these nuclear materials.

In our RBS chamber also a new large area beam sweep option was tested first time (see Fig. 4.). The recycling of the older equipment now allows raster scanning of the higher current, low energy proton beams for up to 4x4 cm^2 areas.

The collaborative ion beam analysis and helium ion microscopy work continued in many fronts. The COVID-19 situation prevented many of the visitors through the RADIATE project but samples did travel and results are now processed. The other collaborations with research institutes and companies stayed active despite the pandemic.

→ Figure 3. RBS spectra of ^{240}Pu sample measured with 2.4 MeV He beam.





↑ Figure 4. After the successful upgrade of the multi-detector RBS chamber on the previous year, the year 2021 started with tests with rastered 4x4 cm^2 beam using few µA, 0.6 MeV proton beam. Beam on target was about 25 µA. This type of setup could be used for example for low energy proton irradiations.

PERSONNEL NEWS

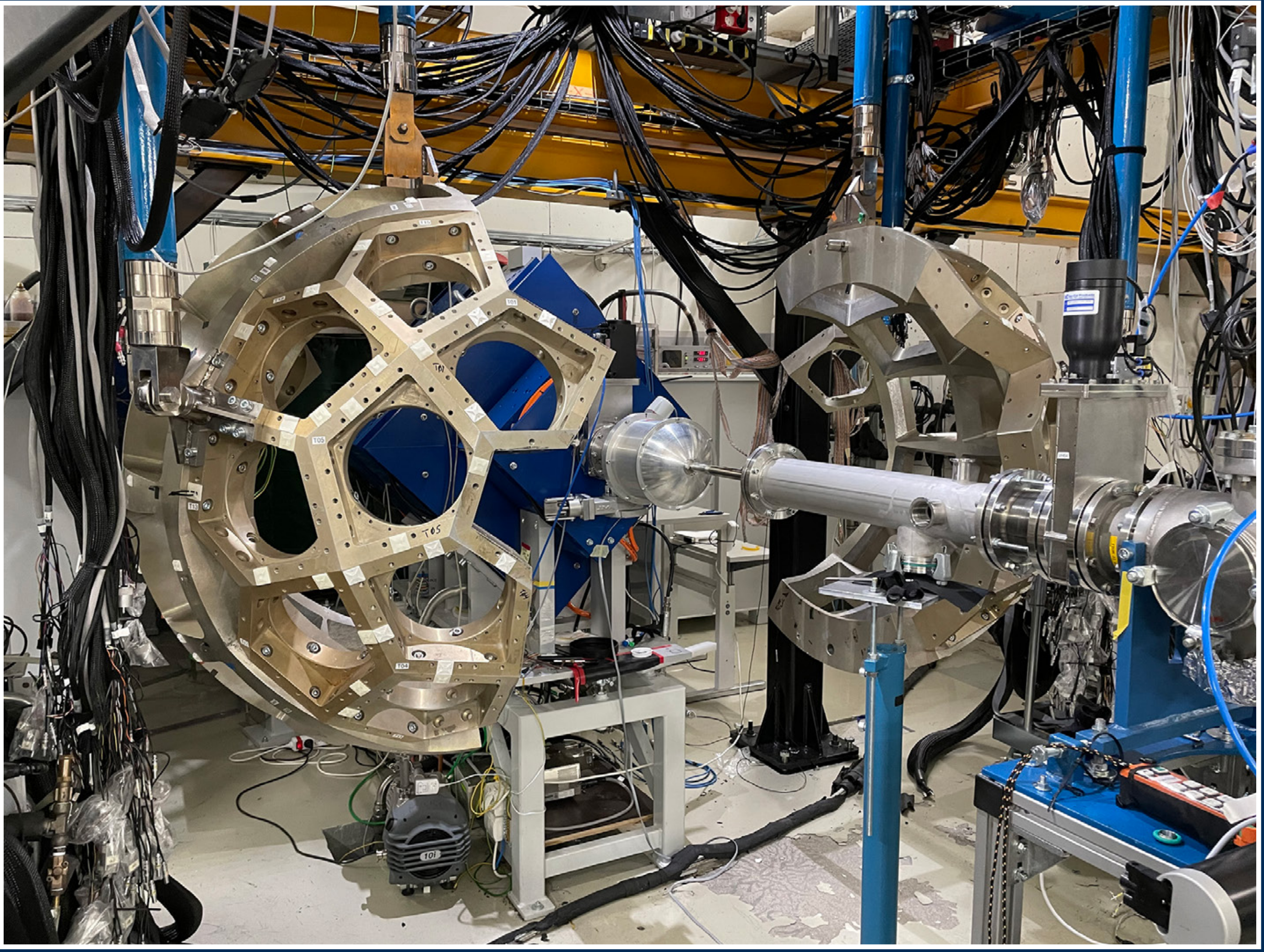
In the beginning of 2021, MSc Mikko Kivekäs started as a doctoral researcher in the Academy research Fellow Dr. Mikko Laitinen's project where the experimental mismatch of the low energy, heavy ion scattering and recoil cross sections are studied. In 1^{st} of September Dr. Kai Arstila started his study leave, which is expected to last until the end of 2023.In October MSc Akbar Hossain started as a doctoral researcher in October. His research is related to the Laser-SNICS project, where also new results were published [4]. Similarly during the October, PhD Kofi Brobbey started to work in HiiletIN-project (coordinated by LUKE) as a post-doc. His main task is to do HIM work and also to help with the tomography work. He will be 50 % working for our group and 50 % for the tomography group. He did his PhD in Åbo Akademi and has been working in Oulu before coming here.

Selected publications

[1] S. Kinnunen, K. Arstila, T. Sajavaara, Al_2O_3 ALD films grown using TMA + rare isotope $^2H_2{}^{16}O$ and $^1H_2{}^{18}O$ precursors, Appl. Surf. Sci. 546, 148909 (2021).

[2] S Kinnunen, M Lahtinen, K Arstila, T Sajavaara, Hydrogen and deuterium incorporation in ZnO films grown by atomic layer deposition, Coatings 11 (5), 542 (2021).

[3] O. Tarvainen, R. Kronholm, M. Laitinen, M. Reponen, J. Julin, V. Toivanen, M. Napari, M. Marttinen, T. Kalvas, D. Faircloth, H. Koivisto, T. Sajavaara, Photo-assisted O^- and Al^- production with a cesium sputter ion source, AIP Conf. Proc. 2373, 020001 (2021).



COSMOLOGY

Professor Kimmo Kainulainen
Senior Lecturer Sami Nurmi

We study fundamental puzzles in the standard cosmological LCDM-model, including nature of Dark Matter, the origin of the baryon asymmetry and the (quantum) origin of the observed large scale structures during inflation and their subsequent evolution.

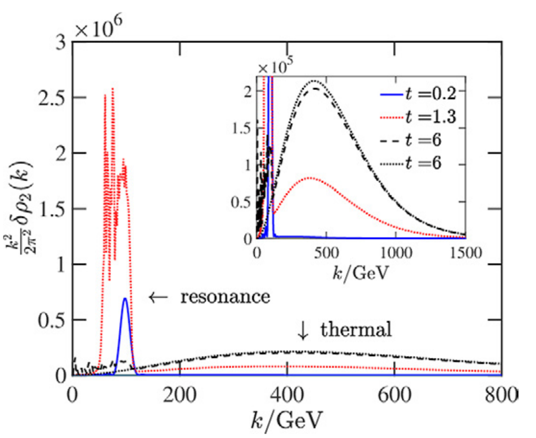
https://www.jyu.fi/science/en/physics/research/highenergy/cosmology

DARK MATTER

About 26% of the total energy of the universe consists of a pressureless fluid, whose precise nature is unknown. We have studied various candidates for this dark matter (DM), ranging from particle DM to Primordial Black Holes (PBHs). Recently we have shown that primordial physics at very high energies can in many ways be connected to DM and its properties testable by precision data of cosmic structures. We have shown that inflation and reheating rather generically affect the abundance and properties of particle DM components in setups with very weak couplings to the SM sectors. Inflation may also source PBHs that would contribute to DM: we have shown that even a small amount of PBHs would significantly affect the growth of structures and constraints on particle DM candidates, e.g. axions [1,2], and their interactions with various astrophysical objects could lead to characteristic observable signals such as fast radio bursts [3].

INFLATIONARY PHYSICS

We investigate the microscopical mechanism of inflation and its connection to fundamental theories of matter and gravity. In particular we study the theoretical foundations and novel observable signals of Higgs inflation models, exploring how inflation constrains the SM and its extensions through high-energy phenomena. We are developing resummed QFT methods to derive precise, testable signals related to various out-of-equilibrium processes, such as particle production during reheating [4]. We also work broadly on topics connected to non-perturbative infrared dynamics of light quantum fields on the inflaton sector and beyond, applying and developing the approximative stochastic formalism and testing it against first principles calculations. We are also studying new features of primordial perturbations that will be tested by future CMB and LSS surveys, quantifying their links to the inflaton sector or other matter fields. This involves e.g. inflation in quantum diffusion dominated regimes, spectral distortion signatures, gravitational waves, and primordial black holes.



↑ Figure 1. The energy density in quantum excitations at different times of a simulation of reheating process. At early times (red and blue lines) distributions are highly non-thermal, peaking at infrared due to resonant particle production. At a very late time (dashed line) the distribution is nearly degenerate with an equivalent thermal distribution (black dotted line). Figure is from [4].

BARYON ASYMMETRY

One of the main problems in ΛCDM-model concerns the origin of the matter-antimatter, or baryon asymmetry in the Universe (BAU). The observed BAU must be created after inflation by some microphysical processes that go beyond the standard model of particle physics. The leading models to explain BAU include the leptogenesis and the electroweak baryogenesis (EWBG) mechanisms. Both scenarios involve treating interacting coherent quantum fields in CP-violating, out-of-equilibrium conditions. We are world leaders in deriving and applying quantum transport methods for calculation of the BAU in these setups; some recent contributions include [5,6] and we are currently extending these methods even further. We are also building generic numerical tools for implementing our transport equations in practical applications.

INHOMOGENEITIES

Perhaps the most puzzling element of the ΛCDM-model is Dark Energy. It is needed to explain the apparent acceleration of the Universe, given the intrinsic assumption of homogeneity and isotropy, but due to nonlinearity of general relativity (GR), it is not clear how precise this assumption is quantitatively. To investigate this issue, we develop numerical methods to simulate the evolution of inhomogeneities in fully nonlinear GR. We will use our simulated inhomogeneous model universes to study the effect of nonlinear structures on cosmological observables and eventually on the inference of the cosmological parameters from observational data.

Selected publications

[1] E.D. Schiappacasse, T.T. Yanagida, Phys.Rev.D 104 (2021) 10, 103020, *https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.103020*

[2] S. Nurmi, E.D. Schiappacasse, T.T. Yanagida, JCAP 09 (2021) 004, *https://iopscience.iop.org/article/10.1088/1475-7516/2021/09/004*

[3] K. Kainulainen, S. Nurmi, E.D. Schiappacasse, T.T. Yanagida, Phys.Rev.D 104 (2021) 12, 123033, *https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.123033*

[4] K. Kainulainen, O. Koskivaara, JHEP 12 (2021) 190, *https://link.springer.com/article/10.1007/JHEP12(2021)190*.

[5] K. Kainulainen, JCAP 11 (2021) 11, 042, *https://iopscience.iop.org/article/10.1088/1475-7516/2021/11/042*.

[6] H. Jukkala, K. Kainulainen, P.M. Rahkila, JHEP 09 (2021) 119, *https://link.springer.com/article/10.1007/JHEP09(2021)119*.

NEUTRINO AND ASTROPARTICLE PHYSICS

Senior Researcher Wladyslaw H. Trzaska

JYFL involvement in experimental neutrino and astroparticle physics started in 2006 when we took the scientific responsibility for the Centre of Underground Physics in Pyhäsalmi. At that time, the European neutrino community envisioned a giant new generation neutrino observatory. The subsequent LAGUNA and LAGUNA-LBNO Design Studies chose Pyhäsalmi as the preferred location for the liquid scintillator detector (LENA) and liquid argon time projection chamber (GLACIER). However, obeying the 2013 European Strategy for Particle Physics ruling, LAGUNA's scientific and technological legacy was transferred to the USA-based DUNE and the Chinese-based JUNO. Our team participates in both projects. In addition, in cooperation with Oulu University, HIP, and NCBJ, Poland, we are operating the NEMESIS experiment in the Callio Lab in the Pyhäsalmi mine attempting indirect detection of Dark Matter WIMPs.

https://www.jyu.fi/science/en/physics/research/highenergy/neutrino-physics

↑ Figure 1. JUNO construction status. View from the bottom (big photo) and from the top (upper inset) of the water pool. Lower inset: cable car at the end of the slope tunnel.

← Figure 2. Part of the Finnish team in front of the NEMESIS setup in August 2021.

There has been significant construction progress in both DUNE and JUNO experiments. While DUNE is still in the early stages, JUNO already completed drill-and-blast excavations in December 2020 and moved to the civil construction's final phase. By August 2021, the concrete layer of the giant water pool was completed, and by the end of the year, the underground halls were delivered to the collaboration. The installation has commenced. The detector area is reachable by a cable train moving along a 1265 m long 42% slope. A vertical shaft elevator will be added soon. Above ground, all the campus buildings are ready.

Finnish contribution to JUNO focuses on radiopurity studies of the liquid scintillator samples. The measurements are done at a depth of 4000 m.w.e. in the Callio Lab in the Pyhasalmi mine. These measurements are especially relevant to the solar pp-neutrino measurements with the OSIRIS/SERAPPIS project.

The NEMESIS (New Emma MEasurementS Including neutronS) experiment, operating since 2019 at a depth of 210 m.w.e. in the Callio Lab at the Pyhasalmi mine, has delivered the first significant results. They were presented at ICRC 2021, the 37th International Cosmic Ray Conference, and at TAUP 2021, the 17th International Conference on Topics in Astroparticle and Underground Physics. We have also analysed neutron spectra from two other experiments: NMDS and ZEPLIN-II. The outcome is both puzzling and intriguing. There are small but consistent anomalies in the neutron spectra from all three measurements. Accounting for differences in neutron detection efficiencies, the positions of the anomalies agree very well. Also, the intensities match when corrected for the acquisition time and detection geometry. Therefore, while the three measurements are inconclusive when analysed separately, taken together, they exclude a statistical fluke to better than one in a million level. The anomalies are consistent with Dark Matter WIMP self-annihilation in the Pb target. We are seeking funding to confirm the anomalies' existence, multiplicity, and intensity above the five-sigma discovery level with an upgraded NEMESIS setup.

Videos
https://youtu.be/XibQj4udohA – presented at VCI 2022
https://youtu.be/0UcEdJje4ms – presented at TAUP 2021

Selected publications

DUNE Collaboration. (2021). Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment. *European Physical Journal C*, *81*(4), Article 322.
https://doi.org/10.1140/epjc/s10052-021-09007-w Open Access

JUNO Collaboration. (2021). The design and sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS. *European Physical Journal C*, *81*(11), Article 973.
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https://doi.org/10.1007/jhep11(2021)102 Open Access

Trzaska, W. H., Enqvist, T., Jędrzejczak, K., Joutsenvaara, J., Kasztelan, M., Kotavaara, O., Kuusiniemi, P., Loo, K., Orzechowski, J., Puputti, J., Słupecki, M., Szabelski, J., Usoskin, I., & Ward, T. (2021). DM-like anomalies in neutron multiplicity spectra. J. Phys.: Conf. Ser. 2156 012029.
http://doi.org/10.1088/1742-6596/2156/1/012029

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Kasztelan Marcin, Enqvist, T., Jędrzejczak, K., Joutsenvaara, J., Kotavaara, O., Kuusiniemi, P., Loo, K.K., Orzechowski, J., Puputti, J., Sobkow, A., Słupecki, M., Szabelski, J., Usoskin, I., Trzaska, W.H., Ward, T.E. (2021). High-multiplicity neutron events registered by NEMESIS experiment. In *ICRC 2021: 37th International Cosmic Ray Conference* (pp. 1-8). Sissa. POS Proceedings of Science, 497.
https://doi.org/10.22323/1.395.0497 Open Access

QCD THEORY

Professors Kari J. Eskola and Tuomas Lappi
Academy Research Fellows Hannu Paukkunen,
Ilkka Helenius and Heikki Mäntysaari

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.

www.jyu.fi/physics/particles/urhic

DEVELOPMENTS IN THE GROUP

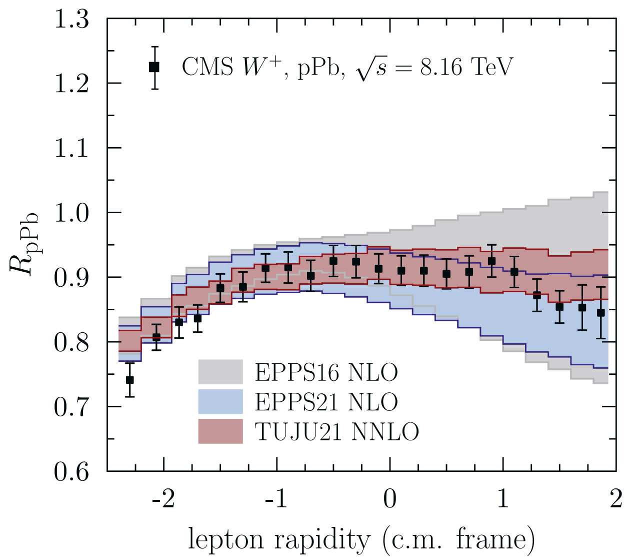
In 2021 Heikki Mäntysaari obtained an Academy of Finland Research Fellowship. Manuel Epele, Petja Paakkinen, Pragya Singh and Marius Utheim started as new postdocs. At the end of the ERC-CoG grant of Lappi, several postdocs moved to new postdoc positions: Meijian Li and Yair Mulian to Santiago de Compostela and Pablo Guerrero Rodríguez to Lisbon. Andrecia Ramnath defended her thesis and moved to a postdoc position in Lund. Henri Hänninen defended his PhD thesis. Mirja Tevio started as a new graduate student. At the end of the year we were, together with the ALICE group, awarded the status of Center of Excellence by the Academy of Finland starting in 2022.

LIGHT CONE WAVE FUNCTIONS WITH MASSIVE QUARKS

A central ingredient in calculations of scattering processes in the high energy saturation regime of QCD is the light cone wavefunction. It is a universal QCD quantity encoding the light cone gauge partonic structure of a high energy projectile, and a necessary ingredient in cross section calculations for different scattering processes. In [1] we reported the calculation of the light cone wave function for a longitudinal virtual photon to split into quark-antiquark states, including for the first time quark masses at one loop accuracy. Such wave functions are fundamental results in QCD perturbation theory. Among all different formulations of perturbative field theory, light cone wave functions for massive particles have been the last ones not yet known at one loop accuracy, until now. The photon light cone wave function is needed in calculations of cross sections for several precision probes of perturbative gluon saturation at the Electron-Ion Collider (EIC). Using our result we derived also the total dipole picture DIS cross section for longitudinal virtual photons with quark masses.

EPPS21 AND TUJU NUCLEAR PDFS

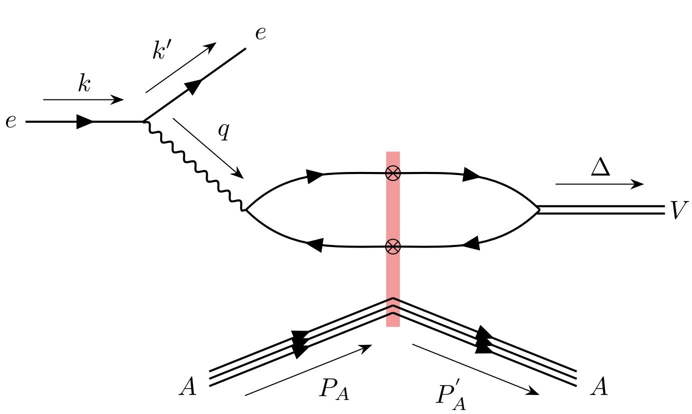
Parton distribution functions (PDFs) encoding the partonic structure of protons and heavier nuclei (nuclear PDFs) at high energies are needed to compute hard-process cross sections in hadronic collisions. In 2021 we completed two major analyses of nuclear PDFs -- EPPS21 [2] and TUJU21 [3] (see Fig. 1). EPPS21 builds on an over-20-year tradition of global nuclear PDF analysis in Jyväskylä and improves our earlier work, EPPS16, by including now also a significant quantity of new experimental data from proton-lead collisions at the LHC. In particular, EPPS21 is the first analysis to successfully establish a global next-to-leading order (NLO) perturbative-QCD study of nuclear PDFs including simultaneously LHC proton-lead data on dijet, D-meson, and electroweak-boson production. On the other hand, with the TUJU21 PDFs, prepared in collaboration with Tübingen University, we took a significant step towards a global nuclear-PDF analysis at next-to-NLO (NNLO) accuracy with LHC observables included. The TUJU21 analysis, embedded in the open-source xFitter framework, augments our earlier TUJU19 PDFs by incorporating LHC proton-proton and proton-lead data on electroweak-boson production in a full-fledged NNLO study. With TUJU21 we also advanced towards our long-term goal of fitting simultaneously proton and heavier-nucleus data in a coherent analysis framework.



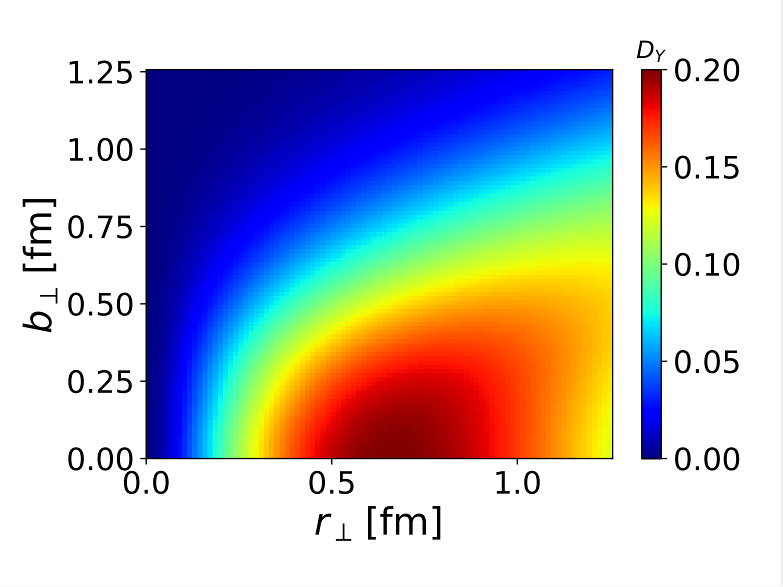
← Figure 1. Nuclear modification of W+ production in proton-lead collisions. The CMS Collaboration data are compared with calculations using EPPS16, EPPS21 and TUJU21 nuclear PDFs.

IMAGING THE NUCLEUS AT HIGH ENERGY

Exclusive scattering processes where exactly one particle is produced are powerful probes of the partonic structure of protons and nuclei, in particular its spatial distribution. In such processes at least two gluons must be exchanged with the target which renders them especially sensitive to the partonic structure. We have studied these processes using two complementary approaches. First, we performed the first perturbative calculation of heavy vector meson production at next-to-leading order (NLO) accuracy in the high-energy limit applying the Color Glass Condensate effective theory of QCD [4] (Fig. 2). These developments will be used to probe the non-linear QCD dynamics in protons and nuclei at high energies. In parallel, we used a collinear factorization-based approach to calculate the cross section for vector meson electroproduction at NLO accuracy [5]. This allows for a simultaneous description of exclusive processes both in ultraperipheral collisions at the LHC and in the future EIC and will enable for a more precise extraction of the proton and nuclear generalized parton distribution functions that include information about the spatial distribution of quarks and gluons. We have also proposed a new observable, azimuthal correlations between the outgoing electron and the produced vector meson in deep inelastic scattering experiments [6], to obtain more differential information about the proton and nuclear color field at high energies (Fig. 3). In particular we have shown that such measurements, possible at the future EIC, probe the spatial correlations in the gluon field.



← Figure 2. Exclusive vector meson production in the dipole picture, figure from [6].



↑ Figure 3. Average dipole amplitude for a proton as a function of dipole size *r* and impact parameter *b*, from Ref. [6].

HOT SPOTS AND SPATIAL STRUCTURE OF QUARK GLUON PLASMA

The internal spatial structure of gluons inside the nucleus determines the distribution of quark matter at the initial stage of a heavy ion collision. This structure is then propagated to azimuthal particle correlations that are observed experimentally. In recent years such azimuthal "flow" structures have also been observed in collisions of not only heavy nuclei, but also protons. The internal structure of the proton is, however, not very well constrained, although it can be measured in exclusive deep inelastic scattering experiments, as discussed above. In [7] we developed an analytically tractable model for the spatial structure of the gluon field in the proton. It combines different physical mechanisms commonly evoked in the literature: the overall size of the proton, a hot spot internal structure, and fluctuating color charges at the microscopical level, into an efficient and simple parametrization.

Importantly, our model enables an analytical evaluation of averages in the different sources of fluctuations. Using this model we calculate, for a proton-nucleus collision, the eccentricities that characterize the azimuthal anisotropy of the initial plasma state. We show that for such small collision systems the hot spot fluctuations in the proton are by far the dominant mechanism of generating azimuthal anisotropy.

Selected publications

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[2] K.J. Eskola, P. Paakkinen, H. Paukkunen, C. A. Salgado, arXiv: 2112.12462 [hep-ph]

[3] I. Helenius, M. Walt, W. Vogelsang, arXiv: 2112.11904 [hep-ph]

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[6] H. Mäntysaari, K. Roy, F. Salazar, B. Schenke, Phys. Rev. D 103 (2021) 9, 094026

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ALICE EXPERIMENT AT THE CERN LHC

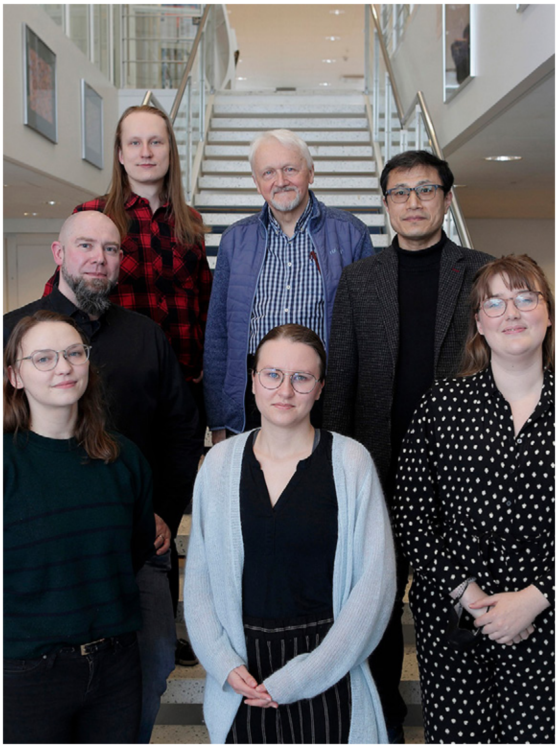
Senior Lecturers Sami Räsänen and DongJo Kim
Senior Researcher Wladyslaw H. Trzaska

ALICE (A Large Ion Collider Experiment) is the dedicated heavy ion detector system at the CERN Large Hadron Collider (LHC). The primary goal of the lead-lead collisions at very high energies is to study the properties of quark-gluon plasma (QGP)– a state of matter where partons are no longer confined inside the hadrons. ALICE has excellent tracking and particle identification capabilities down to very low momenta, allowing for detailed studies of the chemical composition of the matter and other essential properties of the QGP.

The ALICE physics program also includes proton-lead and proton-proton collisions. These lighter combinations provide a reference for Pb-Pb measurements and help to explore the limits of QGP creation with high-multiplicity events in small systems. The year 2022 is eagerly awaited as the LHC will continue measurements after the long shutdown during which experiments, particularly ALICE, underwent major upgrades.

ALICE (A Large Ion Collider Experiment) collaboration has ~1950 members from 172 institutes in 40 countries. JYFL and HIP have been ALICE members since November 1997.

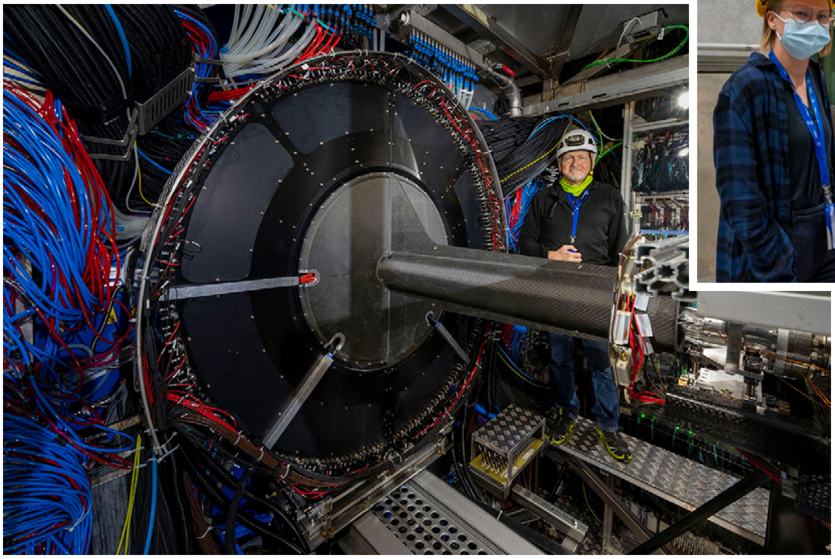
https://www.jyu.fi/science/en/physics/research/highenergy/nuclear-reactions



In 2021 ALICE completed a significant upgrade preparing for the start of the LHC Run 3 (2022-2025). The expected Pb–Pb instantaneous luminosity will increase by a factor of 6, and the minimum-bias Pb–Pb interaction rate will be ~ 50 times more than the heavy-ion collision rate during Run 2. To cope with such a drastic change and achieve the proposed physics objectives, ALICE implemented several improvements and installed three new detectors, including the Fast Interaction Trigger (FIT) – the main timing and trigger detector. Currently, our group holds the primary responsibility for the FIT.

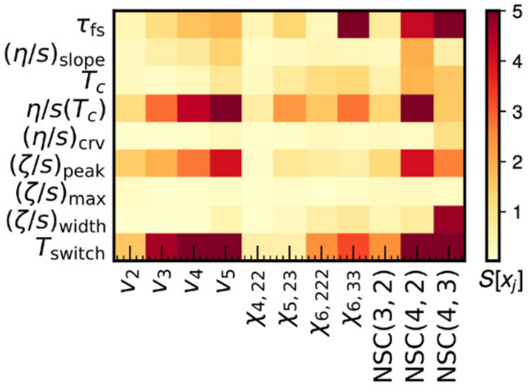
FIT is essential for ALICE operation. It was designed to provide input for the new ALICE Central Trigger Processor, monitor luminosity, determine the collision time, and provide an unbiased sample of the forward multiplicity needed to extract the centrality and the reaction plane required in the analysis of heavy-ion collisions. The Finnish team collaborates with 19 institutions from 9 countries in these tasks. To ensure FIT completion, installation, and commissioning, two of our group members stayed full-time at CERN in 2021. The schedule was extremely tight, but the detector was ready for October's first LHC test collisions. The FIT project attracted much attention in CERN media with dedicated articles in the EP Newsletter, CERN bulleting, and ALICE News [1].

↓ Figure 1. W.H. Trzaska (FIT Project Leader) next to FIT-A array ready for LHC Run 3, December 2021.



↑ Figure 2. H. Rytkönen (left) and L. Huhta in front of the FoCal test beam setup at CERN SPS in September 2021.

In the physics data analysis, we are one of the leading groups in the analysis of collective flow in ALICE. The matter created in Pb-Pb collisions has a complex structure containing hot spots and cooler regions. This leads to anisotropic pressure gradients in the matter, followed by a measurable modulation in the momentum distributions that the detectors observe. One can relate these observations to transport properties of the QGP, like shear and bulk viscosities, with hydrodynamical simulations. However, as the parameter space is large and simulations require very sizable computing time, one can restrict the physical parameters with Bayesian estimation. In 2021, we published two Bayesian analyses [2] that received very positive attention both inside ALICE and in the heavy ion community at large.



↑ Figure 3. Sensitivity of experimental observables (x-axis) to parameters characterizing QGP matter properties (y-axis). Figure taken from [2].

We worked on dijet mass distributions in pp and p-Pb collisions at low jet momenta. These measurements give further restrictions to jet energy losses in the small systems. We will extend these studies to Pb-Pb where clear interactions with jets and dense medium created in the collision has been observed.

Two of our team members were awarded a CERN Fellow position in 2021. Jasper Parkkila defended his PhD-thesis in November 2021 on Bayesian studies and flow analysis in ALICE and moved to CERN Team in the beginning of 2022. Maciej Slupecki, our current post-doc, will join the CERN Beam Department in July 2022. We participated actively in international conferences and presented both instrumental work [3,4] and physics analysis results.

The Academy of Finland awarded the QCD theory group and experimental ALICE group with a Centre of Excellence in Quark Matter at the end of 2021. This is the first CoE on LHC physics in Finland and will strengthen our resources for the next eight years.

Selected publications

[1] Fast Interaction Trigger (FIT) in the CERN media:
EP Newsletter *https://ep-news.web.cern.ch/content/new-alice-fast-interaction-trigger* ;
CERN bulleting *http://bulletinserv.cern.ch/bulletin/564/* ;
ALICE News *https://alice-collaboration.web.cern.ch/node/35196*

[2] J.E. Parkkila, A. Önnerstad, and D.J. Kim, Phys.Rev.C 104 (2021) 5, 054904, arXiv 2106.05019 [hep-ph] ; arXiv 2111.08145 [hep-ph]

[3] M. Slupecki for the ALICE Collaboration, Status of the Fast Interaction Trigger for ALICE Upgrade, PoS(ICHEP2020)779, *https://pos.sissa.it/390/779/pdf*

[4] H. Rytkönen for the ALICE Collaboration, Event plane determination with the new ALICE FIT detector, PoS(ICHEP2020)814 *https://pos.sissa.it/390/814/pdf*

INDUSTRIAL COLLABORATION

Professors Ilari Maasilta and Timo Sajavaara
Senior Researchers Arttu Miettinen and Arto Javanainen
Staff Scientist Heikki Kettunen

The Thermal nanophysics group has well established collaborations 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. In 2021, collaboration with globally leading nanofabrication tool companies continued, in particular with Raith GmbH.

The Complex Materials group is involved in industrial collaboration through the openly accessible X-ray Tomography laboratory. There, several experiments for domestic and international companies have been made during the year. The scope of these collaborations is often the determination of the microstructural properties of novel biomaterials and the troubleshooting of production processes. A particularly interesting topic has been the characterization of fibre networks in various environmental conditions like elevated relative humidity, and under specific stress states and histories. Collaboration with the VTT Technical Research Center of Finland and other members of the FinTomo network has been continued.

The Radiation Effects group of the Accelerator Laboratory continued the utilization of the RADEF facility under ESA's Technical Research Programme (TRP). The contract was again renewed in 2020 and will continue until the end of 2022. In the contract, we are obliged to offer K-130 cyclotron beam time for ESA and the European space industry. In addition, we provide irradiation tests with our LINAC electron accelerator. The use of RADEF's commercial beam time in 2021 was 1488 hours corresponding to 24 % of the total running hours of the K-130 cyclotron. In total, 57 test campaigns for 21 companies were performed at RADEF. The commercial revenue in 2020 was about 900 k€.

RADEF is involved in several EU and ESA projects. The Horizon 2020 Marie-Curie (MSCA) RADSAGA training network, started 2017, 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 Erasmus Mundus Joint Master Degree programme (RADMEP) and EU Horizon-2020 project called "RADiation facility Network for the EXploration of effects for indusTry and research" (RADNEXT) started in 2021. Two ESA projects; Estimation of proton induced Single Event Effect rates in very deep submicron technologies and Radiation Characterisation of EEE components for ESA space applications, started in 2020. In these ESA projects, RADEF acts as subcontractor.

The delivery of the entire TOF-ERDA end-station and data acquisition system, worth more than 0.5M€, was scheduled to take place already in 2021 but was realized in early 2022 due to COVID-19 related delays of different components. Despite COVID-19 or perhaps even partially due to it, the commercial analysis services using ToF-ERDA were very actively used by companies with samples arriving on a weekly basis.

The atomic layer deposition (ALD) activities towards industry continued under the umbrella of the ALD CoCampus together with the JAMK University of Applied Sciences. The joint projects Lisäävä and iADDVA funded by EU regional funds brought together several companies interested in 3D printing and ALD. The City of Jyväskylä joined the active discussion and planning with JYU and JAMK in 2021, and new initiatives for ecosystems fostering growth and creating jobs in industry will start in 2022.

TEACHER EDUCATION AND PHYSICS EDUCATION RESEARCH

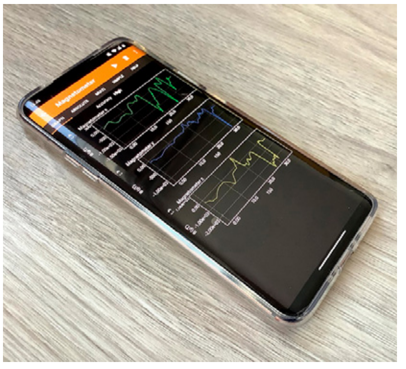
Professor Pekka Koskinen
Senior Lecturer Antti Lehtinen

This annual report is the first one to describe the activities of the newly established *Teacher Education and Physics Education Research* group. Unlike other, well-defined groups at the department, our group is a semi-coherent assembly of physicists active in teacher education and educational research. The group provides physics subject teacher students a mental home and highlights the department's physics education research and teaching development activities, which have gained momentum and attention during the recent years. We work in close collaboration with the Departments of Education and Teacher Education.

https://www.jyu.fi/science/fi/fysiikka/tutkimus/opettajakoulutus

DIGIPHYSLAB PROJECT

As a part of the group's activites, Antti Lehtinen coordinates the Erasmus+ -funded (2021 – 2023) project "Developing Digital Physics Laboratory Work for Distance Learning" (DigiPhysLab, *www.jyu.fi/digiphyslab*). The project was initially spurred on by the move to distance learning due to the COVID-19 pandemic. DigiPhysLab aims to support physics instructors globally in developing their instructional lab tasks via developing 1) a framework to categorize these sorts of distance learning lab tasks and 2) 15 piloted instructional lab tasks that can be used in a distance learning setting. The other project partners are University of Göttingen in Germany and University of Zagreb in Croatia. Currently first tasks have been piloted by each partner of the project and framework is nearing completion. Most of the tasks include using the sensors included in modern smartphones for the measurements. DigiPhysLab also ties into the larger development of the instructional labs at the Department. The tasks developed in the project already fulfill our vision for labs: experimental skills come first, and the students' agency is supported via open-ended elements.



↑ Figure 1. An example of data collection using a smartphone.

SCAN: SELF-ASSESSMENT METHOD FOR LEARNING THE PROBLEM-SOLVING PROCESS

In working life, physicists perform modeling and calculations of problems with unknown answers. Therefore, physicists need to gain confidence in their own doings and the ability to identify and correct own mistakes. To nurture these skills also during studies, we developed a technology-enhanced self-assessment -based Solve-Correct-Assess-Negotiate (SCAN) method to assess problem solving (*ruotiminen* in Finnish). In our investigations of the method, we found, for example, that students who perceived SCAN beneficial adopted a deeper approach to learning and experienced more support than earlier.

Selected publications

[1] Lehtinen, A., Hähkiöniemi, M., & Nieminen, P. (2021). Guiding Student Thinking Through Teacher Questioning when Learning with Dynamic Representations. In *Virtual and Augmented Reality, Simulation and Serious Games for Education* (pp. 111-121). Springer, Singapore.

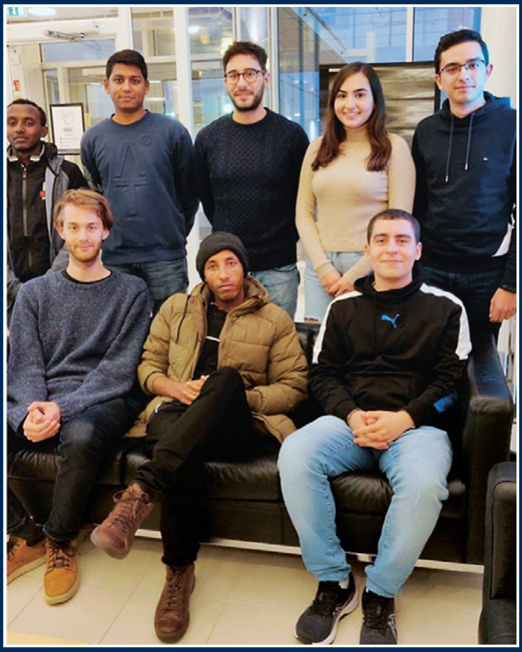
[2] J. Lämsä, A. Virtanen, P. Tynjälä, J. Maunuksela, and P. Koskinen *SCAN: A self-assessment method for learning the problem-solving process in higher education* (submitted)

PHYSICS EDUCATION

Professor Pekka Koskinen
Academy Research Fellow Heikki Mäntysaari
Senior Researcher Arto Javanainen
Doctoral students Miha Luntinen and Topi Löytäinen

We educate physicists at the bachelor, master, and doctoral levels in all our research areas: experimental, theoretical, and computational nanoscience, nuclear and accelerator-based physics, cosmology, particle physics, and teacher education (for statistics, see page 4).

Our nanoscience education is conducted together with the departments of chemistry and biological and environmental science. Our experimental facilities at the Nanoscience Center and the Accelerator Laboratory are popular visiting sites for elementary and upper secondary school classes, with hundreds of eager students annually getting excited about contemporary physics research.



↑ Figure 1. Part of the RADMEP class of 2021–2023. Three students arrived later in the semester due to Covid19-related problems in their visa and travel arrangements.

THE FALL OF 2021 BROUGHT THE FIRST RADMEP STUDENTS TO JYU

The five-year Erasmus Mundus Joint Masters Degree programme *Radiation and its Effects on MicroElectronics and Photonics Technologies* (RADMEP) provides a multidisciplinary and innovative master-level education in interactions between radiation and microelectronics and photonics. The RADMEP program has two goals: to improve career prospects for its students and to respond to the needs of the industry, agencies and society. Thanks to this program, students will develop useful professional and soft skills in the rich European cultural context.

The first intake of RADMEP had 11 students from 9 different countries. RADMEP students start their MSc studies at JYU in the fall semester. After this for the spring semester they will move to KU Leuven (KUL), Belgium. Their second-year studies will continue in France, either in University of Montpellier (UM) or St. Etienne (UJM), depending on their specialization track (Microelectronics or Photonics). During their last semester (spring of 2nd year) they will carry out their Master thesis work, in any of the four universities (JYU, KUL, UM or UJM) or with the associated partners involved in the project.

More information on the RADMEP programme can be found at *https://master-radmep.org/*.

INTERNATIONAL PHYSICS OLYMPIADS

The department has a long tradition for selecting and training advanced upper secondary school students to represent Finland in various international physics competitions. In 2021, we participated in the Nordic-Baltic Physics Olympiad (online) and the 51th International Physics Olympiad organized by Lithuania, with the Finnish team joining remotely from the Physics department. Due to the COVID restrictions training camps for students were held online. As a significant part of our training focuses on experimental methods, the online format allowed us to completely review our curriculum. We also developed and published material that fits well to the upper secondary school curriculum and is easy to use for teachers who want to provide extra support for their advanced students (see *www.jyu.fi/ipho*).

RESEARCHERS' NIGHT

Senior Researcher Janne Pakarinen

The sixth Researchers' Night event at the Department of Physics was organized on 24.9.2021. In response to the COVID-19 related social distancing measures, only a limited number of participants were allowed on site. They could join in a number of laboratory tours or interactive workshops run by students and staff members. All events were fully booked, and, without restrictions, we would have reached a similar flow of participants as in earlier years.

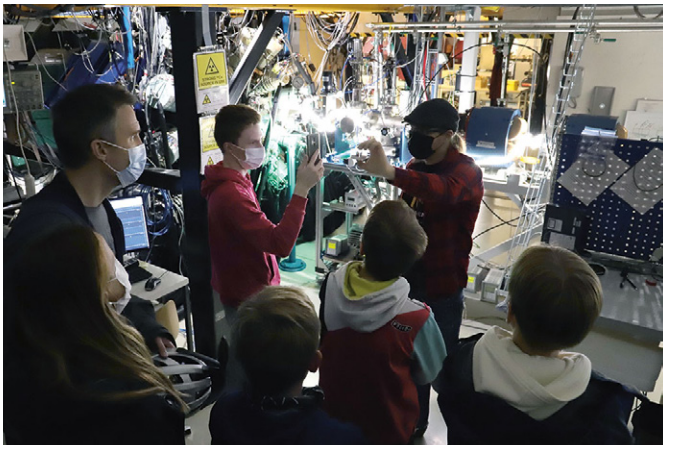
In one of the engaging workshops run by Sami Räsänen and his team, it was shown how simple ingredients, such as plastic cup, kitchen cloth and a piece of dry ice could be used to visualize cosmic rays and radon in the room air. These miniature DIY cloud chambers raised eyebrows of many visitors spanning the whole demographic range.

Another hit was the 3D imaging workshop by Arttu Miettinen and the tomography group. They had set-up their X-ray microtomography device to reveal hidden secrets of items brought by visitors.

To reach out to persons who could not book their place in the physical event, a virtual tour in the Accelerator Laboratory was organized. It was hosted by a popular YouTuber Joona Leppälä, also known as ZoneVD. His captivating and enthusiastic touch to research and science attracted more than 3 000 followers in the Instagram live stream. The live stream was a sequel to his earlier YouTube-episode at the Accelerator Laboratory that is reaching nearly 40k downloads.

ZoneVD Instagram live Researchers' Night:
https://youtu.be/zbBDZBRH-XQ

ZoneVD YouTube episode prior to Researchers" Night:
https://youtu.be/jlKzO2jRN8Q



↑ Figure 1. Kalle Auranen revealing the secrets of nuclear physics to the Researchers' Night visitors and people following it through ZoneVD's Instagram Live.
(Photo by J. Pakarinen)

↑ Figure 2. Excitement in the air, when does an event appear in the cloud chamber?
(Photo by J. Pakarinen)

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