JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

ANNUAL REPORT 2020
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 from the Nanoscience Center, located next to the Department and housing part of our personnel. Our Department is highly international and we collaborate with numerous universities and research institutes abroad, such as CERN.

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UNIVERSITY OF JYVÄSKYLÄ

HEAD OF DEPARTMENT

FOREWORD

This Annual Report provides a summary of the activities at the Department of Physics during the year 2020[1].

The research at Department of Physics at University of Jyväskylä is carried out in two main areas, subatomic physics and materials physics. These generic research entities both include a variety of topics that utilize methods of theoretical, computational and experimental physics. Materials physics includes several branches of nanophysics and applied materials physics. Subatomic physics features nuclear physics, particle physics and cosmology. Research in nanophysics concentrates in the interdisciplinary Nanoscience Center that is a joint research entity involving two other departments of the Faculty of Natural Sciences and Mathematics, the Departments of Chemistry and of Biological and Environmental Sciences. Experimental research in nuclear and particle physics is carried out in the Accelerator Laboratory and in several major European research centers. Subatomic physics and multidisciplinary nanophysics are among the core research areas of the Faculty, and continue being supported by several profiling actions carried out by the University.

The year 2020 will be long remembered as a peculiarity among all the years in the history of the Department of Physics since its foundation in 1965. Starting mid March and continuing through the rest of the year and until now, a full year later, the Covid-19 pandemic has forced the personnel of the Department to adapt into restrictions and constantly changing practices concerning their work conditions and working modes. The change was especially remarkable concerning the teaching personnel and students that experienced an abrupt transition from normal to full remote mode teaching within a few days in March. Yet, they managed to complete this forced transition successfully and have carried through the curriculum as planned and with minor detriments, as is already now evident. The scientific activity and productivity of the Department also remained at high level. As an indication of that, the total amount of publications produced was about 300. As a single example of the impact of publication activities, I wish to mention an earlier work of the JYFL QCD group introducing the "EPS09" nuclear parton distribution functions[2]) which, as the first Finnish theoretical particle physics article, reached the milestone of 1 000 citations during the year 2020. Another excellent achievement to mention is the five-year ERC starting grant funding to Associate Professor Juha Muhonen, working in experimental nanophysics.

In spite of severe restrictions to travelling, active international and national collaborations have been maintained, and have contributed to the results achieved. In addition to mainstream academic research, the department has continued actively in applied research and industrial collaboration. In particular the commercial activity in radiation safety consulting service offered to companies and institutions, in accordance with the new radiation safety law, was established and reached considerable volume during the year 2020. I sincerely want to congratulate the personnel and the students at the Department of all these achievements over this troubled year.

During the year 2020, the senior staff of the Department was strengthened as Pekka Koskinen was appointed to the position of a full professor. His field of research is in computational nanophysics and in research of teaching. He is also a Vice Head of Department responsible for teaching and outreach. In addition, Antti Lehtinen started his 3-year term as a Senior Lecturer position shared

[1] The Department has produced an annual report every year since 1976. The reports since the year 2000 are available in electronic form in: *https://www.jyu.fi/science/en/physics/current/annual-reports*

[2] K.J. Eskola, H. Paukkunen, C.A. Salgado, EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions, JHEP 0904 (2009) 065

2020

ANNUAL REPORT
Department of Physics

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JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

with the Department of Teacher Education, thereby amending development and research of teaching at the Department. Furthermore, two new Associate Professors (tenure track), Tuomas Grahn and Markus Kortelainen were appointed in the fields of experimental and theoretical nuclear physics, respectively, and Senior Lecturer Hannu Paukkunen in the field of particle physics. At the same time the longtime radiation safety officer, Chief Engineer Jaana Kumpulainen retired, and was followed by Sami Rinta-Antila in this duty. Jaana will, however, continue to support the Department within the commercial radiation safety consulting activities.

The financial result of the Department in 2020 ended slightly positive as the minor downward fluctuation of competitive external funding was compensated by operational savings, mainly in travel costs. The financial status was stabilized by core funding which no more showed decline, and by the success in raising external funding during the previous year, coming in full use this year. I consider the strong financial status as another indication of the high quality of the work of the entire personnel.

Finally, I wish to thank the colleagues at the Department of Physics of these nearly three years that I had the privilege to work as the Head of Department. I have truly enjoyed working with all of you in this position. I am confident that the Department will continue to prosper under the new leadership and wish all the best to the new Head of Department, Professor Timo Sajavaara, and to the new Vice Head of Department responsible for research and infrastructure, Professor Ilari Maasilta.

Markku Kataja
HEAD OF DEPARTMENT 1.1.2018 – 30.11.2020

For me the year 2020 ended quite differently than I had foreseen when I was elected to be the head of Physics department for 13 months. When I was asked for this position in rather short notice, my initial answer was “no” and I had many good reasons for this answer including interesting research projects and a puppy at home. But then I gave another big thought about it, what different kind of insight this position would give to university and finally decided to be available.

As Markku has told above, the department is in many ways in good shape: the research is of excellent quality and the teaching has developed significantly over the past couple of years. One clear reason is the quality of the leadership: I have seen from close Markku’s devotion to the department and his fair and listening way of leading the department. Wisdom, one could say. The department is very grateful to Markku for his years first as the vice-head and then as the head of department. It was easy to take the control of this moving train which has plenty of momentum and clear direction.

The coming years will bring challenges such as the Ylistö renovation and decreasing number of starting students. Although the renovation is expected to bring discomfort, it will bring us updated and upgraded working, teaching and laboratory space. That, together with our teaching and research efforts will surely increase the numbers of interested students in the coming years. The spirit of our department is a positive one and that will carry far.

Timo Sajavaara
VICE-HEAD OF DEPARTMENT 1.1.2018 – 30.11.2020
HEAD OF DEPARTMENT 1.12.2020 –

STATISTICAL DATA FROM 2020

151
PERSONNEL

- Professors incl. associate professors **17**
- University lecturers and researchers **30**
- Postdoctoral researchers **35**
- Doctoral students **34**
- Technical staff **28**
- ERC grantees **3**
- Academy professors **1**
- **+** Several research assistants (MSc students)

Personnel counted in person-years

~345
UNDERGRADUATE STUDENTS
of which new students **46**
Doctoral students **67**

32 BSC DEGREES	**27** MSC DEGREES
1 PHLIC DEGREES	**11** PHD DEGREES

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

63 NUMBER OF FOREIGN VISITORS	**76** INCOMING VISITS	**36** VISITS ABROAD

~290 Peer reviewed publications	**~260** A1-A3 articles	**~30** A4 Conference proceedings	**~10** Other publications

CONFERENCE AND WORKSHOP CONTRIBUTIONS
Invited talks **~50** | Other talks **~120** | Posters **~10**

14.3
FUNDING (million €)

- Basic funding **8.3**
- Sales (contract research) **0.9**
- Income according to separate laws (mainly EU funding) **2.0**
- Government grants **2.9**
- Other income **0.2**

CONTENTS

Editors:
Kari J. Eskola, Tuomas Lappi, Minttu Haapaniemi

Cover picture
Jan Sarén, University of Jyväskylä

THE YEAR 2020 AT THE NSC

Tero Heikkilä

When I was asked to write this piece on NSC's year 2020, I noticed that it was hard to remember what actually happened. During the remote working period, days have been filled with research and its organization, but they all seem the same. It has been as in the film Groundhog Day, where the main character is forced to experience the same day over and over.

Before the pandemic we had built some great NSC-wide traditions and events – and our coffee room had just been renovated to help organize them. The idea was to lift the community spirit and lower thresholds for communication. Because of the pandemic almost all of the events had to be cancelled. Nanoscience Center is an international organization, as one third of its employees comes from outside Finland. I believe those events were especially important for those who do not have relatives or family living nearby.

Luckily the absolute lockdowns in Jyväskylä have been short and we have been able to carry on most of the time with experimental activities on-site, although reduced. We have learned new tools, how to annotate in Zoom, and how to maintain discussions in online meetings. We have had some fruitful NSC-wide online meetings, both on research and around it. Together with JYU communication services and in collaboration with the media house Keskisuomalainen, we established a well-functioning method to spread information to the public and organized events on the scientific information about coronaviruses and on Nobel Prizes. Several thousands of people followed these events, more than what we could reach with traditional platforms. If we wish we can now participate in more meetings than ever before because of their online format. But it is difficult to evaluate the effect of remote working on a creative mind needed in research. I believe that creativity is enforced by social interaction, even among natural scientists, and even among the theorists. Therefore, the biggest influence of the pandemic on research has been its negative effect on our creativity.

I mention a few randomly selected physics-oriented NSC highlights from last year: Pekka Koskinen was promoted to a full professor position in the fall. Pauli Virtanen (with his coauthors) published two already now widely cited papers on Python-based tools for scientific computing, arising as side results of physics projects. One of the papers was within *Altmetric's list of 100 most discussed scientific papers in the world*. We were for the third time involved in the university profiling program, and received funding that allowed us to open two positions, one in synthetic nanochemistry and another on atomic resolution scanning probe methods. Those positions are open as of this writing. Interestingly, from all universities in Finland, University of Jyväskylä has the most profiling initiatives on natural sciences. We also were able to install some major new infrastructure, such as the Bluefors dilution refrigerator that allows studying quantum optics effects at millikelvin temperatures.

In the film, the eternal Groundhog Day finally ended when the main character learned to accept the situation (and fell in love with the woman). I am not willing to accept social distancing in the long term (but falling in love is ok). Rather, I hope that vaccinations will help us back to the more normal life sooner than later. And once that happens, I will strongly support common activities, both related to research and socializing. And I hope to meet with as many of you as possible. Face to face.

THERMAL NANOPHYSICS

Professor Ilari Maasilta

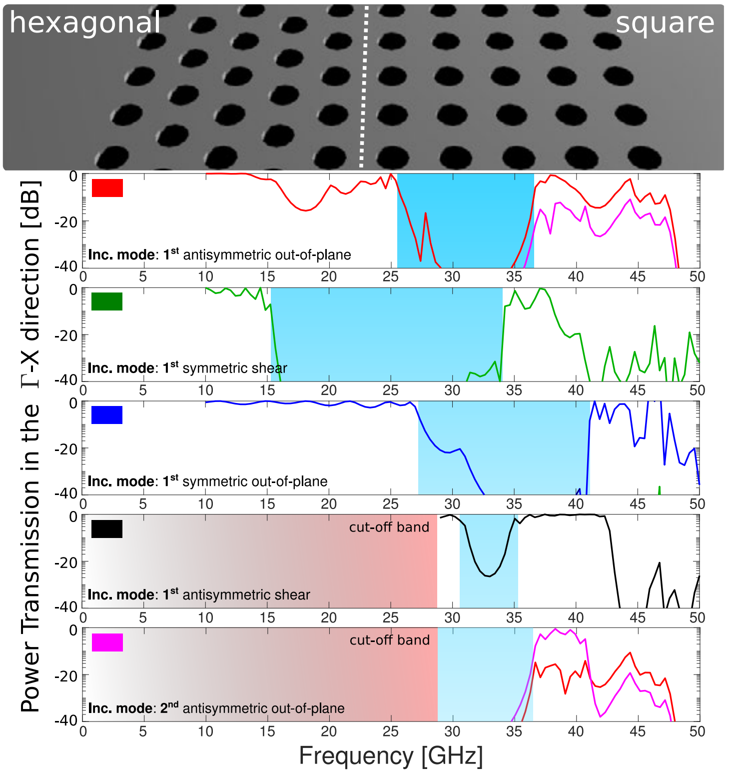
The group is one of the main users of the nanoscience center (NSC) nanofabrication infrastructure, and has currently three main research directions:

- Nanoscale thermal transport, especially focusing on phononic crystals and near-field transport
- Development of superconducting materials and devices, especially ultrasensitive superconducting radiation detectors and superconducting tunnel junctions
- Utilizing novel nanofabrication and imaging techniques for interdisciplinary projects, such as nanoscale biological imaging with helium ion microscope (HIM) and 3D laser lithography

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

NANOSCALE THERMAL TRANSPORT

We continue to have a strong focus on the theory and experiments of nanoscale thermal transport. In 2020, we obtained the first published results on a new collaboration with NASA Goddard Space Flight Center and SRON Netherlands Institute for Space Research, where the goal is to integrate nanoscale holey phononic crystal (PnC) membranes with ultrasensitive superconducting radiation detectors known as kinetic inductance detectors (KIDs), to increase their sensitivity. The idea is based on the concept that the detector performance improves, if we design a phononic band gap at the dominant phonon emission frequency, corresponding to twice the energy gap of the superconductor (recombination phonons). In a numerical study [Puurtinen2020], we demonstrated with 3D elastic wave scattering simulations that a finite size composite PnC assembled from two simple hole patterns (square and hexagonal lattice) can reach at least 40 dB power attenuation level for the recombination phonons. This was estimated to result in the improvement of the detector sensitivity by an order of magnitude.



↑ Figure 1. Top: A composite phononic crystal structure containing cylindrical holes in square and hexagonal lattice configurations. Bottom: Transmitted phonon power through the composite structure with normal incidence.

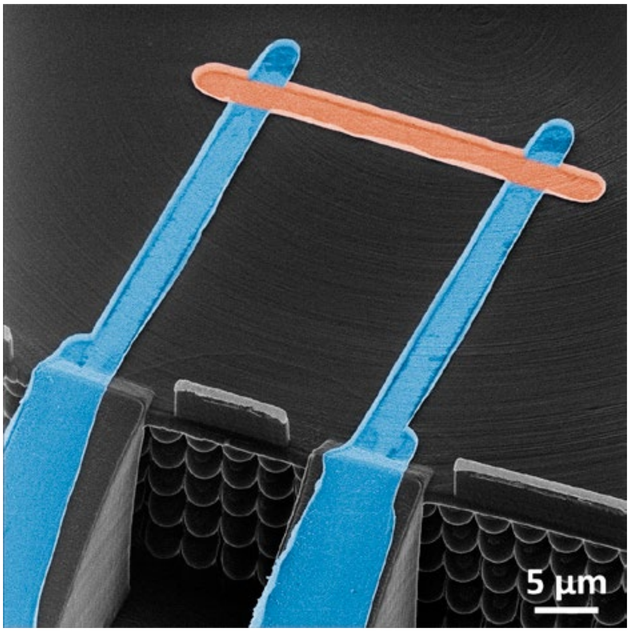
DEVELOPMENT OF SUPERCONDUCTING DEVICES AND MATERIALS

In the past, we have been developing devices and fabrication techniques with the unique tools of the nanofabrication facilities at the Nanoscience Center, such as with the helium ion microscope and the 3D lithography tool. In 2020, we applied our recently developed techniques to fabricate structures on uneven substrates using 3D laser lithography [Heiskanen2020a] to the fabrication of superconducting tunnel junctions [Heiskanen2020b]. This result opens up many possibilities to integrate superconducting components into more varied environments which possibly help to improve the performance of various sensors, quantum bits etc. We have used the technique to integrate thermometers with 3D phononic crystal structures for thermal transport experiments. The editors of Applied Physics Letters felt that the article [Heiskanen2020b] was noteworthy, and chose it to be promoted as an Editor's Pick.

Our group's role in the collaborative EU FET project SUPERTED developing a novel superconducting-ferromagnetic (SF) thermoelectric radiation detector also continued during 2020. We continued the implementation of the measurement setup for X-ray detection using SQUID amplifiers [Geng2020], and initiated fabrication work to integrate superconducting absorbers into the SF tunnel junction devices. In addition, data analysis techniques for superconducting detectors were further developed [Helenius2020].

NOVEL NANOFABRICATION AND IMAGING TECHNIQUES FOR INTERDISCIPLINARY PROJECTS

The interdisciplinary collaboration with biologists has continued in 2020, which saw the start of a new project, where the goal is to use biological self-assembly of bacterial colonies for photonic and phononic applications. In addition, we published very recently the first review article on the biological applications of helium ion microscopy (HIM) [Schmidt2021], in collaboration with scientists from the Helmholtz-Centre for Environmental Research in Leipzig, Germany and the University of Bristol, UK.



↑ Figure 2. False-color helium ion micrograph of a superconducting tunnel junction on top of a three-dimensional structure, fabricated using 3D direct-write laser lithography.

Selected publications

[Puurtinen2020] T.A. Puurtinen, K. Rostem, P.J. de Visser and I. J. Maasilta, *A Composite Phononic Crystal Design for Quasiparticle Lifetime Enhancement in Kinetic Inductance Detectors*, J. Low Temp. Phys. 199, 577 (2020)

[Heiskanen2020a] S. Heiskanen, Z. Geng, J. Mastomäki, and I. J. Maasilta, *Nanofabrication on two- and three-dimensional topography via positive-tone direct-write laser lithography*, Adv. Eng. Mater. 22, 1901290 (2020)

[Heiskanen2020b] S. Heiskanen and I.J. Maasilta, *Superconducting tunnel junction fabrication on three-dimensional topography based on direct laser writing*, Appl. Phys. Lett. 117, 232601 (2020)

[Geng2020] Z. Geng, A. P. Helenius, T. T. Heikkilä, I. J. Maasilta, *Superconductor-ferromagnet tunnel junction thermoelectric bolometer and calorimeter with a SQUID readout*, J. Low Temp. Phys. 199, 585 (2020)

[Helenius2020] A. P. Helenius, T. A. Puurtinen, K. M. Kinnunen, and I. J. Maasilta, *Simultaneous Noise and Impedance Fitting to Transition-Edge Sensor Data using Differential Evolution*, J. Low Temp. Phys. 200, 213 (2020)

[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)

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.

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

TRANSPORT IN MWNTS

Arc-discharge synthesized multiwalled carbon nanotubes (AD-MWNT), or related MWNTs, exhibit a good quality compared to the more common type of MWNT synthesized by catalytic CVD methods. Yet experimental measurements on these are rather few and typically have not correlated data from different measurement techniques. In a collaborative work [1], we reported Raman spectroscopy, Scanning probe microscopy, conductivity measurements, and Force microscopy on single AD-MWNTs. The results demonstrate the high quality of AD-MWNTs and are compatible with the view of them as the best approximation of MWNTs as an assembly of defect-free concentric individual SWNTs. We also demonstrated conductance measurements over a step on the surface of an AD-MWNT, which is due to an abruptly broken outer layer(s), whereby the interlayer resistance is measured (Figure 1).

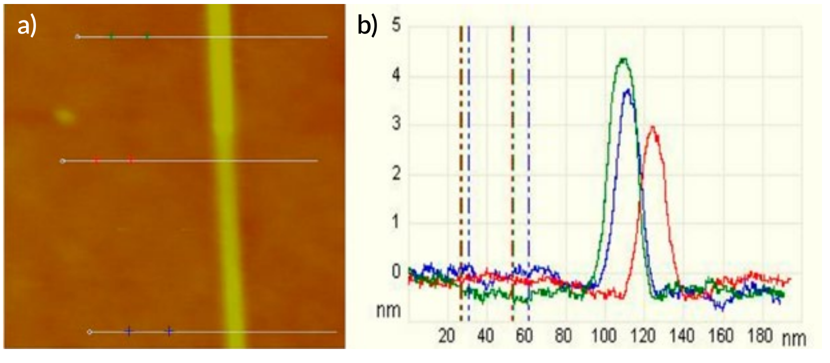
FUNCTIONALIZED CARBON NANOTUBES

Our studies on CNT-based molecular complexes, especially on CNTs solubilized in water with hemicellulose (xylan) has continued. Previously we investigated the transport properties of thin films casted from such very stable water based dispersions of CNTs [2]. Presently we are interested in exploring experimentally at the molecular level the character of the CNT/xylan complexes. This is pursued in collaboration with the Scanning probe group at the KU Leuven in Belgium.

Selected publications

[1] 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)

[2] Shao Dongkai, Peerapong Yotprayoonsak, Ville Saunajoki, Markus Ahlskog, Jorma Virtanen, Veijo Kangas, Alexander Volodin, Chris Van Haesendonck, Maria Burdanova, Connor D.W. Mosley, James Lloyd-Hughes, *Conduction properties of thin films from a water soluble carbon nanotube/hemicellulose complex*, Nanotechnology, **29**, 145203 (2018)



← Figure 1. a) AFM image of an AD-MWNT section with a step. The step (and the thicker section) is just above the middle line. b) Height profiles across the tube along the lines in image (a).

MOLECULAR ELECTRONICS AND PLASMONICS

Associate Professor Jussi Toppari

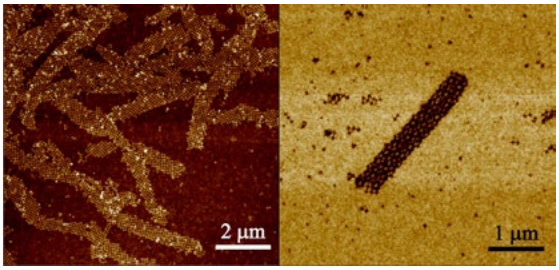
The group studies nanoelectronics, -plasmonics, and -photonics, concentrating on phenomena involving molecules as active components or as building blocks. We continue developing our long experience on self-assembled DNA structures and their utilization in fabrication of electrical and plasmonic nanodevices. This year we started a new project aiming for a large-scale self-assembled DNA tile lattices to produce optical metasurfaces for detection and optical manipulation. This is a continuation and further development for our earlier DNA assisted lithography method [1], which was also recently improved in collaboration with Aalto University [2]. In addition, we study a strong coupling between confined light, like surface plasmons and cavity photons, and molecules, concentrating on a new field of polaritonic chemistry. We have made an extensive set of measurements with the results just submitted, but also have been involved in the development of the theory in collaboration with Prof. Heikkilä (JYU) [3]. Other activities include improving surface enhanced Raman spectroscopy (SERS) [4], and studying plasmonic properties of graphene, in which we also started a new project this year. During the year 2020 also a long-term collaboration with Prof. Lehto (UEF) on utilization of carbon nanotube-functionalized porous silicon particles on Li-ion battery electrodes was concretized in a form of joint publication [5].

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

SURFACE-ASSISTED HIERARCHICAL SELF-ASSEMBLY OF DNA TILES

DNA nanotechnology offers unparalleled precision encoding complex shapes and programmability using a strategy of the bottom-up approach. However, the translation of the high resolution spatial information of DNA constructs to metal nanostructures has been limited long time despite many tries and studies. Quite recently, we and the collaborators have developed the DNA-assisted lithography (DALI) method to create metal structures with desirable optical properties via DNA-origami technology [1,2].

The success of DALI relies on the capability to selectively grow SiO_2 on the bare silicon substrate leaving DNA origami–shaped silhouettes in the layer. To improve this process, we systematically investigate the growth characteristics and required conditions to obtain a homogeneous silica layer suitable for a lithographic mask for metal deposition. Furthermore, our goal is to extend this method to periodic large lattices, again through the hierarchical self-assembly of DNA origami on the solid substrate, as shown in Figure 1. The produced 2D fishnet lattice is assembled via blunt-end interactions. We expect that, following the DALI procedure, these structured lattices will enable a creation of plasmonic metasurfaces with predetermined optical properties.



↑ Figure 1. Atomic force microscope images of cross tile DNA-origami lattices self-assembled on Si surface (left), and similar DNA-origami lattice after the SiO_2 growth around it (right). Height scales are 4.5 nm and 22 nm for left and right images, respectively.

GRAPHENE PLASMONICS FOR SURFACE ENHANCED INFRA-RED SPECTROSCOPY

Until nowadays, surface-enhanced infrared absorption (SEIRA) strategies have been utilizing metallic substrates, such as roughened metal island films or fabricated arrays of small metallic antennas, where molecules are located within the enhanced IR near-field in the vicinity of the structures. The enhancement scales as $|E|^2$ of the local field. Since the surface enhanced Raman spectroscopy (SERS), scales as $|E|^4$, it has even more benefitted from this approach, and even single-molecule SERS sensitivities has been achieved. Since the selection rules of these two spectroscopies are complementary, there is a substantial motivation to enhance SEIRA to similar single-molecule or few-molecule sensitivity.

Noble metals, however, suffer from poor field enhancement in IR. Hence, it is crucial to investigate other materials that will benefit SEIRA. Among its other outstanding properties, graphene is capable of supporting plasmonic excitations in THz to Mid-IR range which, unlike for commonly used noble metals, can be tuned post-fabrication by electrostatic or chemical doping. On top of that, graphene offers an order of magnitude smaller confinement of coupled electromagnetic fields, leading to a greater enhancement. The two-dimensional nature of graphene enables a relatively simple geometrical pattering with a variety of methods. The patterning influences the two primary aspects of graphene plasmons: the resonant frequency and local field intensity. Thus, the proper choice of fabrication method and careful process development is essential to achieve sufficient enhancement for SEIRA.

We investigate the capabilities of maskless direct-writing patterning of graphene by using energetic ion beams, such as He and Ne. In principle, these methods can achieve a greater resolution compared to conventional techniques such as e-beam lithography, while also eliminating the need to use chemical resist that inevitably leads to a contamination of graphene. Ion beam milling is, however, a highly destructive approach, and careful selection of doses and substrates is necessary.

Selected publications

[1] B. Shen, V. Linko, K. Tapio, S. Pikker, T. Lemma, A. Gopinath, K.V. Gothelf, M.A. Kostiainen, J. J. Toppari, *Plasmonic nanostructures through DNA-assisted lithography*, Science Adv. 4, eaap8978 (2018)

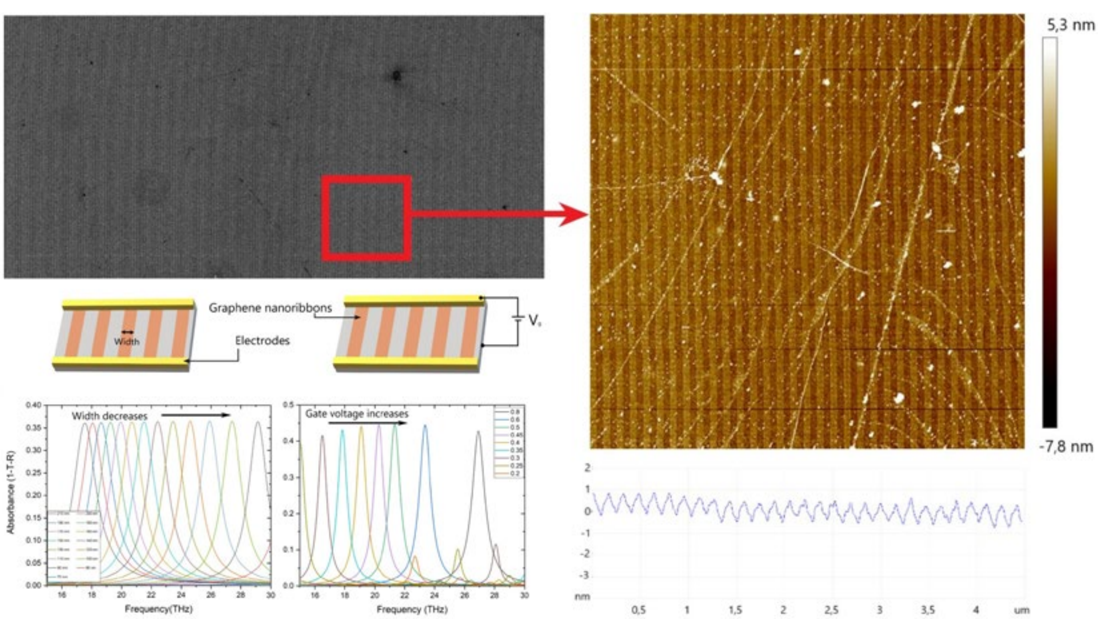
[2] P. Piskunen, B. Shen, A. Keller, J. J. Toppari, M. A. Kostiainen, V. Linko, *Biotemplated Lithography of Inorganic Nanostructures (BLIN) for Versatile Patterning of Functional Materials*, ACS Appl. Nano Mater. 4, 529 (2021)

[3] K.S.U. Kansanen, J. J. Toppari, and T.T. Heikkilä, *Polariton response in the presence of Brownian dissipation from molecular vibrations*, J. Chem. Phys. 154, 044108 (2021)

[4] A. Dutta, T. Nuutinen, K. Alam, A. Matikainen, P. Li, E. Hulkko, J. J. Toppari, H. Lipsanen, G. Kang, *Fabrication-friendly polarization-sensitive plasmonic grating for optimal surface-enhanced Raman spectroscopy*, J. Eur. Opt. Soc.-Rapid Publ., 16, 22 (2020).

[5] T. Ikonen, N. Kalidas, K. Lahtinen, T. Isoniemi, J. J. Toppari, E. Vázquez, M. A. Herrero-Chamorro, J. L. G. Fierro, T. Kallio, V.-P. Lehto, *Conjugation with carbon nanotubes improves the performance of mesoporous silicon as Li-ion battery anode*, Sci. Rep. 10, 5589 (2020).

↓ Figure 2. Helium Ion Microscope and AFM images of Ne-ion milled graphene ribbons on silicon substrate. Schematics show the calculated effect of the ribbon width and electrostatic doping on the graphene plasmon resonance in IR.



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 develop quantum technologies using silicon, the material that is already ubiquitous around us in computers, mobiles and all everyday electronics and hence provides unique possibilities for integrating the quantum components with existing photonic or electronic circuits. The motivation for our research is both in enabling practical quantum sensors and quantum computing components of the future and in probing fundamental physics in these on-chip quantum physics testbeds.

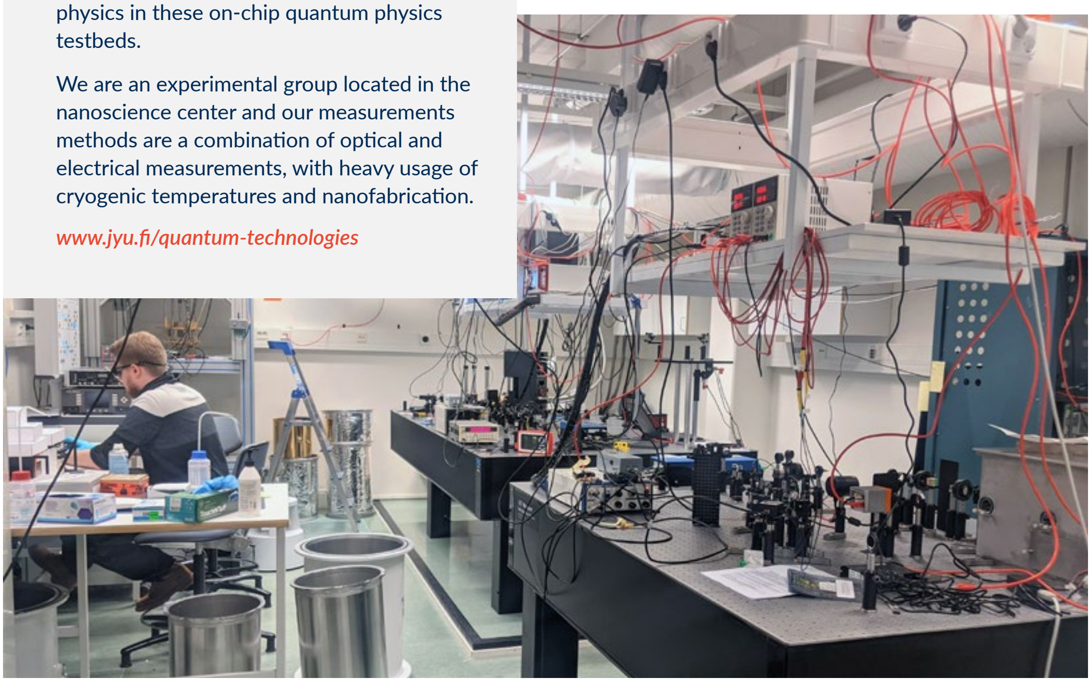
We are an experimental group located in the nanoscience center and our measurements methods are a combination of optical and electrical measurements, with heavy usage of cryogenic temperatures and nanofabrication.

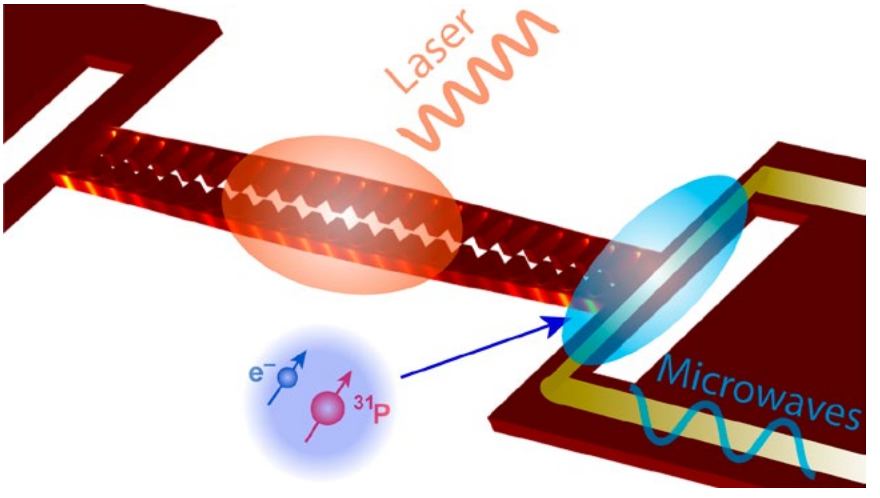
www.jyu.fi/quantum-technologies

THE GROUP GROWS AND THE LAB FILLS UP

The Hybrid Quantum Technologies got its first two PhD students in 2019 and in 2020 we grew in numbers by 150% to a five person (+PI) group. The laboratory has now been basically filled with equipment, additions this year include an optically accessible dilution refrigerator capable of 10 mK temperatures and a new smaller optical table with a new tunable diode laser.

↓ Figure 1. The Hybrid Quantum technologies lab was an empty room just 2 years ago.





↑ Figure 2. An artistic impression of the nanomechanical quantum transducer.

NANOMECHANICAL QUANTUM TRANSDUCERS BETWEEN SPINS AND LASER LIGHT

The spin of a single donor atom in silicon has recently been shown to be one most promising quantum bit platforms in solid-state [1,2]. It combines good quantum properties (long coherence times, excellent control fidelities) with practical, widely used fabrication methods. Silicon, as the underpinning material for current electronics industry and a material with significant commercial photonics activity, provides unique possibilities for integrating the quantum components with ancillary photonic or electronic circuits. Hence, silicon spin qubits are seen as a very promising platform for both quantum sensors and quantum computing.

Silicon spins however have a crucial weakness: they do not have optical transitions that could be used to convert the spin quantum information to optical photons for long distance coupling and readout. Our group's focus is especially in trying to bridge this gap by coupling the spins to a mechanical resonator that can then be in turn coupled to optical fields.

The coupling from the mechanical resonator to optical photons can be done using photonic crystal structures in silicon. The photonic crystals be used to define optical cavities which can then couple the vibrations of the silicon resonator into the light field, down to the single quantum level. These are called optomechanical structures and we have studied a particular implementation of them previously [3,4].

Our group focuses on studying these different quantum systems in silicon and especially in creating new kinds of quantum hybrid systems by coupling spins and mechanical and photonic elements and advancing the uses of the photonic crystal structures for both optomechanics as well as photonics. The ultimate goal is to produce new functionalities for quantum sensing and quantum computing as well as an on-chip testbed for creating and studying semi-macroscopic quantum states. We have received funding for the projects from both the European Research Council (ERC) and the Academy of Finland.

Selected publications

[1] Muhonen *et al.*, *Storing quantum information for 30 seconds in a nanoelectronic device*, Nat. Nanotechnol. **9**, 986 (2014)

[2] Muhonen *et al.*, *Quantifying the quantum gate fidelity of single-atom spin qubits in silicon by randomized benchmarking*, J. Phys.: Condens. Matter **27**, 154205 (2015)

[3] Leijssen *et al.*, *Nonlinear cavity optomechanics with nanomechanical thermal fluctuations*, Nat. Commun. **8**, ncomms16024 (2017)

[4] Muhonen *et al.*, *State preparation and tomography of a nanomechanical resonator with fast light pulses*, Phys. Rev. Lett. **123**, 113601 (2019)

COMPLEX MATERIALS

Professor Markku Kataja

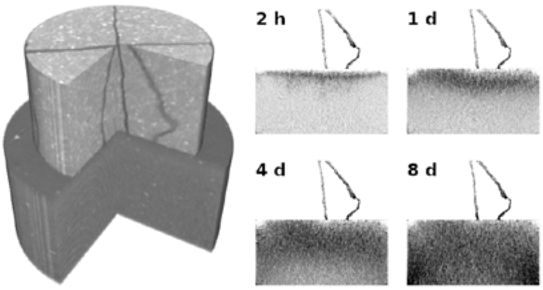
www.jyu.fi/science/en/physics/research/materials-physics/complex-materials

MONITORING MECHANICAL EVOLUTION OF BENTONITE USING X-RAY IMAGING AND TOMOGRAPHY

Bentonite is a natural clay material which is planned to be used as a sealing and protecting material between spent nuclear fuel canisters and the bedrock in Finnish and Swedish nuclear waste repository concepts. As a quite complex material, it poses severe challenges to modelling needed in long-term safety assessment of the concept. Therefore, accurate experimental data on the hydromechanical behavior and transport properties of bentonite are needed.

In 2020, the Complex Materials research group was involved in three bentonite research projects. The Beacon project (funded by EU) aims to understand how initial density differences, induced e.g. by installation gaps between bentonite blocks or voids between bentonite pellets, are homogenized during the wetting process. Our aim in this project was to conduct a set of experiments, where compacted bentonite samples were allowed to swell and fill gaps above the samples. The closure of the gap and the subsequent homogenization process were monitored using X-ray imaging. Another EU project, EURAD HITEC, focuses on temperature effects on clay barriers. High-level nuclear waste produces a considerable amount of heat, which raises temperatures and may have an effect on the hydro-mechanical properties of bentonite. We have studied this by monitoring the wetting of compacted bentonite samples at different temperatures (20–90 °C) using 4D X-ray tomography (three spatial dimensions and time). Furthermore, Broctio is a national project funded by Ministry of Economic Affairs and Employment of Finland that investigates bentonite-rock interaction. Our research focuses on transport phenomena (both bentonite and water) at the bentonite-rock interface. We have conducted constant volume wetting experiments, where compacted bentonite samples are wetted through fractures and cracks in rock samples with water pressures up to 4 MPa. The wetting of bentonite and its swelling into the fractures are again monitored using 4D X-ray tomography.

In order to retrieve the necessary information using X-ray techniques the samples are first imaged in the dry state and thereafter multiple times during the wetting process. Digital image correlation is used to find the displacement field of the solid material, which allows to calculate the solid content distribution at each time step. The corresponding water content distributions are calculated from the difference images that contain information of the total attenuation, taking into account the effects of deformation of the solid material. The methods require careful X-ray beam calibration procedures, which are now implemented in the measuring protocol of the in-house built X-ray microtomographic device 'JTomo'. This new device has been heavily used in the EURAD HITEC and Broctio projects during 2020, and has proven to be very effective in such research.



↑ Figure 1: Left: X-ray tomographic image of a block of cracked rock on top of a bentonite sample. Right: Cross sections of the contact surface at various times showing the wetting process by water flow through the crack into the bentonite sample. Darker shades of gray in the bentonite indicate higher water content.

COMPUTATIONAL NANOSCIENCE

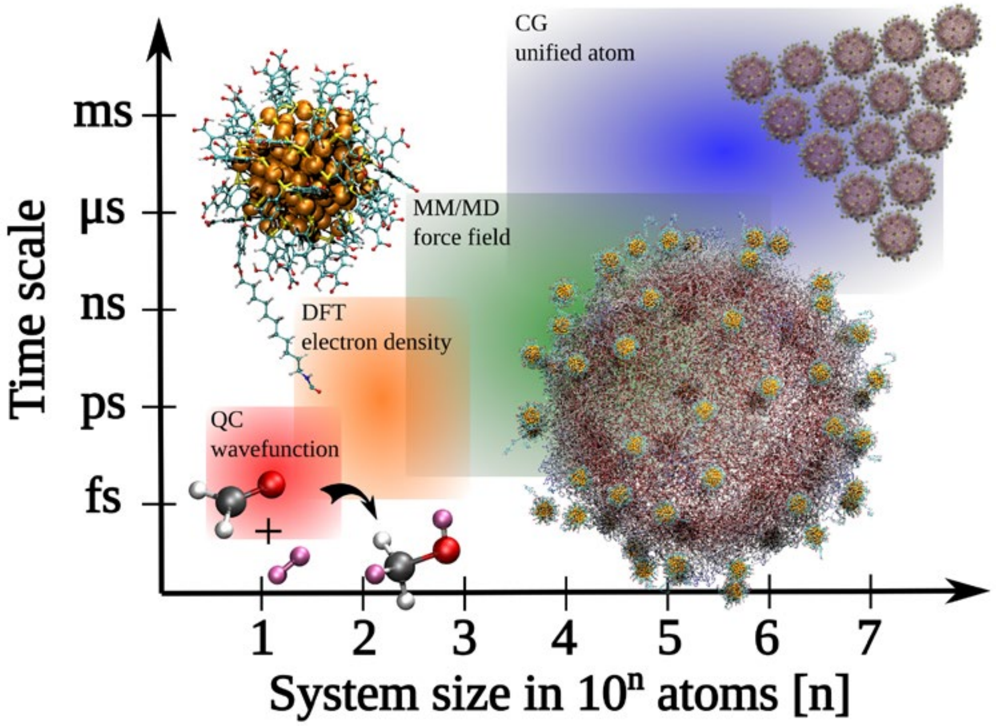
Professor Hannu Häkkinen

We investigate physical and chemical properties of various nanosystems using computational techniques based on density functional theory, dynamical simulations and artificial intelligence. Our current main interest is to understand physical, chemical, catalytic and bio-compatible properties of atomically precise, monolayer-protected metal clusters (MPCs) and their self-assemblies. These "hybrid" well-defined nanoparticles constitute novel nanomaterials with potential applications in plasmonics, catalysis, biological imaging, sensing, and drug delivery (Figure 1). Our group interacts with several computational and experimental groups in Finland and around the world.

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

MPCs are hybrid metal nanoparticles consisting of a metal core and a protecting layer of organic ligand molecules. They have a precise mass and chemical composition, and in many cases their structure is known to atomic precision. The precise knowledge of the MPCs' atomic structure creates an excellent starting point to use various atomistic simulation

↓ Figure 1. The computational nanoscience group is investigating MPCs, having a metal core of gold, silver or copper, and protected by organic molecules, as novel nanomaterials with tuneable physico-chemical properties for diverse potential applications. Group members, from top left clockwise: Hannu Häkkinen, Sami Malola (senior scientist), Nisha Mammen (post doc), Kyunglim Pyo (post doc), Maria Francisca Matus (post doc), Omar Lopez Estrada (post doc), Elli Selenius (PhD student, graduated 12/2020), Maryam Sabooni (PhD student), Antti Pihlajamäki (PhD student), Alessia Marrone (Erasmus exchange student), Joona Huttunen (BSc student)



↑ Figure 2. System size vs. time scales and relevant simulation methods from molecules to self-assembled MPC nanostructures. Quantum-chemical (QC) methods can conveniently deal with small molecules with great accuracy. Density functional theory (DFT) is a major workhorse dealing with MPC's electronic structure, optical properties and reactions, but with limited time scales. Classical force fields generated for molecular mechanics (MM) and molecular dynamics (MD) simulations can give valuable details on MPC-environment interactions such as with viruses as shown here. Finally, processes and properties in self-assembling MPC systems may need to be dealt with coarse-grained (CG) methods where each MPC is described as a "unified atom".

tools to understand their structure-property relations. However, MPCs can have complex interactions with their environments which creates challenges to simulations due to a wide range of relevant length scales, time scales or need to describe the complex chemical interactions properly on an equal footing (Figure 2).

Recently, our group has been part of several such new MPC discoveries [1–6]. Simulations using the density functional theory (DFT) are essential to understand details of catalytic mechanisms [1], to predict new structures [2], to interpret complex photoelectron spectra [3], to understand electronic structure and conductivity in cluster-based 1D materials [4], or to understand coupling of plasmons in MPC assemblies [5]. The role of machine learning (ML) will become increasingly important for enhancing the numerical efficiency of simulations at the DFT level of accuracy as well as providing bridges between methods, as we recently demonstrated by creating a DFT-based atomistic ML force field for a thiolate-protected gold cluster suitable for Monte Carlo simulations of its thermal properties [6].

Selected publications

[1] A. Longo et al., Chem – Eur J **26**, 7051 (2020).

[2] M.F. Matus et al., Chem. Comm. **56**, 8087 (2020).

[3] Y. Tasaka et al. , J. Phys. Chem. Lett. **11**, 3069 (2020).

[4] P. Yuan et al., Nature Comm. **11**, 2229 (2020).

[5] E. Selenius et al., Phys. Rev. B. **102**, 195433 (2020).

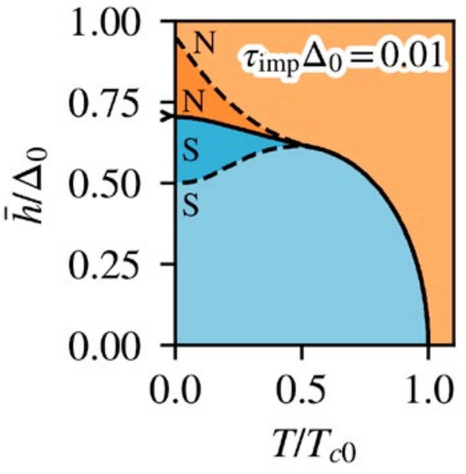
[6] A. Pihlajamäki et al., J. Phys. Chem A **124**, 4827 (2020).

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 phenomenological low-energy theory of quantum systems. In each project we work in close collaboration with world-leading experimental groups, and our goal is both to predict observables and to find out the key elements underlying the previous measurements.

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



↑ Figure 1. The phase diagram of a thin superconductor/ferromagnetic insulator bilayer with impurities. At low temperatures, a first-order phase transition between normal (N) and superconducting (S) states appears as a function of exchange field and temperature, and the size of the multistable region depends on the impurity scattering rate.

QUASICLASSICAL FREE ENERGY OF SUPERCONDUCTORS

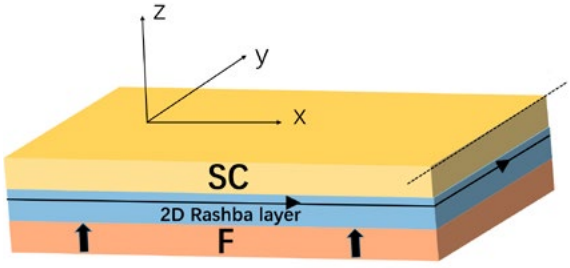
A formulation of the low-energy theory of superconductors, the "quasiclassical theory", has had a long-standing question about how the free energy can be expressed directly in terms of the momentum-integrated Green functions. A partial answer was given in a paper by G. Eilenberger already in 1968, but limited to a specific type of superconductors. A connection to the Luttinger-Ward functional was also established, but the expressions contained an inconvenient integration over an auxiliary coupling constant. In a manuscript [1] published in Phys. Rev. B, we resolve the integration analytically, and obtain the generalization of Eilenberger's result. We show that the result offers a straightforward way to describe e.g. how the superconducting phase transition changes from a second-order to a first-order transition in superconductor/ferromagnetic insulator bilayers as the impurity concentration increases.

MAKING AND MAINTAINING OPEN-SOURCE LIBRARIES FOR SCIENTISTS

Open-source software plays today an important role not only in many aspects of everyday life, but also in scientific research and teaching. One widely used computational environment is based on the Python programming language, and associated libraries, with many commonly needed scientific methods provided by NumPy and SciPy. The two have been developed by a large international loosely organized and interdisciplinary team during the past 20 years, with a long-time involvement by Nanoscience Center University Researcher Pauli Virtanen. Their history, current progress, and some future outlooks have been recently reviewed in two articles published in Nature [2] and Nature Methods [3].

EFFECT OF DISORDER ON MAJORANA LOCALIZATION IN TOPOLOGICAL SUPERCONDUCTORS: A QUASICLASSICAL APPROACH

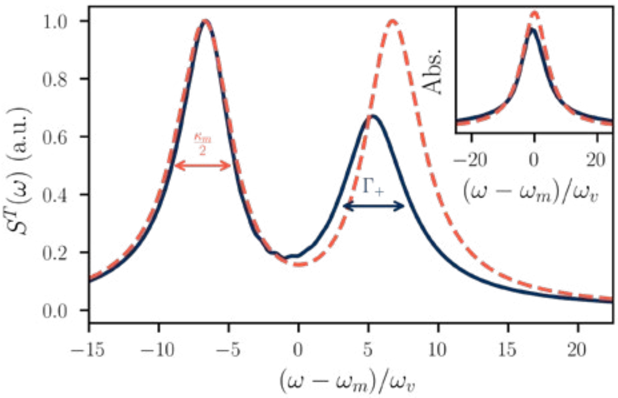
The realization of topological superconductors (TSs) supporting Majorana modes (MMs) in condensed matter systems has attracted much attention due to its potential application in quantum computing. As random impurities are variantly present in any realistic systems, understanding the effect of disorder on the Majorana localization length is of great importance and interest. Plenty of works have been devoted to studying the effect of disorder on MMs in one-dimensional (1D) p wave superconductors. However, we are not aware of a previous study on the effect of disorder in 2D TSs realized in SO coupled systems. In a manuscript [4] published in Phys. Rev. B, we develop a quasiclassical theory to study the effect of disorder on Majorana localization length in 2D TSs. We find a nonmonotonic behavior of the Majorana localization length as a function of disorder strength. At weak disorder, the Majorana localization length decreases with an increasing disorder strength. Decreasing the disorder scattering time below a crossover value, the Majorana localization length starts to increase.



↑ Figure 2. Sketch of the system under consideration. 2D Rashba layer sandwiched by a superconducting thin film and a ferromagnetic insulator.

VIBRATIONAL DISSIPATION IN MOLECULAR POLARITONICS

When organic molecules interact with a confined electromagnetic field their properties including chemical reactivity may change. However, this kind of a strong coupling can only be confirmed by optical means. We investigate the optical response of such a system in detail while taking into account the vibrational modes of the molecules and their dissipation [5]. Our results provide signatures of the presence of the vibrational modes as well as a model to which the experiments can be compared.



↑ Figure 3. Example of polariton spectrum with (blue solid line) and without vibrations (orange dashed line). The inset shows the corresponding molecular absorption profiles.

Selected publications

[1] P. Virtanen, A. Vargunin, M. Silaev, Phys. Rev. B 101, 094507 (2020)

[2] C.R. Harris, K.J. Millman, S.J. van der Walt, R. Gommers, P. Virtanen, et. al., Nature 585, 357 (2020)

[3] P. Virtanen, R. Gommers, T.E. Oliphant, M. Haberland, T. Reddy, et. al., Nature Methods 17, 261 (2020)

[4] Y. Lu, P. Virtanen and Tero Heikkilä Phys. Rev. B 102, 224510 (2020)

[5] K. S. U. Kansanen, J. J. Toppari, and T. T. Heikkilä, J. Chem. Phys. 154, 044108 (2021)

QUANTUM MANY-BODY THEORY

Professor Robert van Leeuwen

We develop formalism and tools that can be used to study quantum systems in which interparticle correlations and time-dependence play an important role. Recent developments include a new perturbation theory for positive spectral functions and number conservation in partially self-consistent theories. Another ongoing project is to deepen the understanding of the mathematical foundations of density functional theory and develop new methods and functionals that are tested on analytically solvable systems. A third research line is concerned with non-equilibrium systems in which electron-boson interactions are important.

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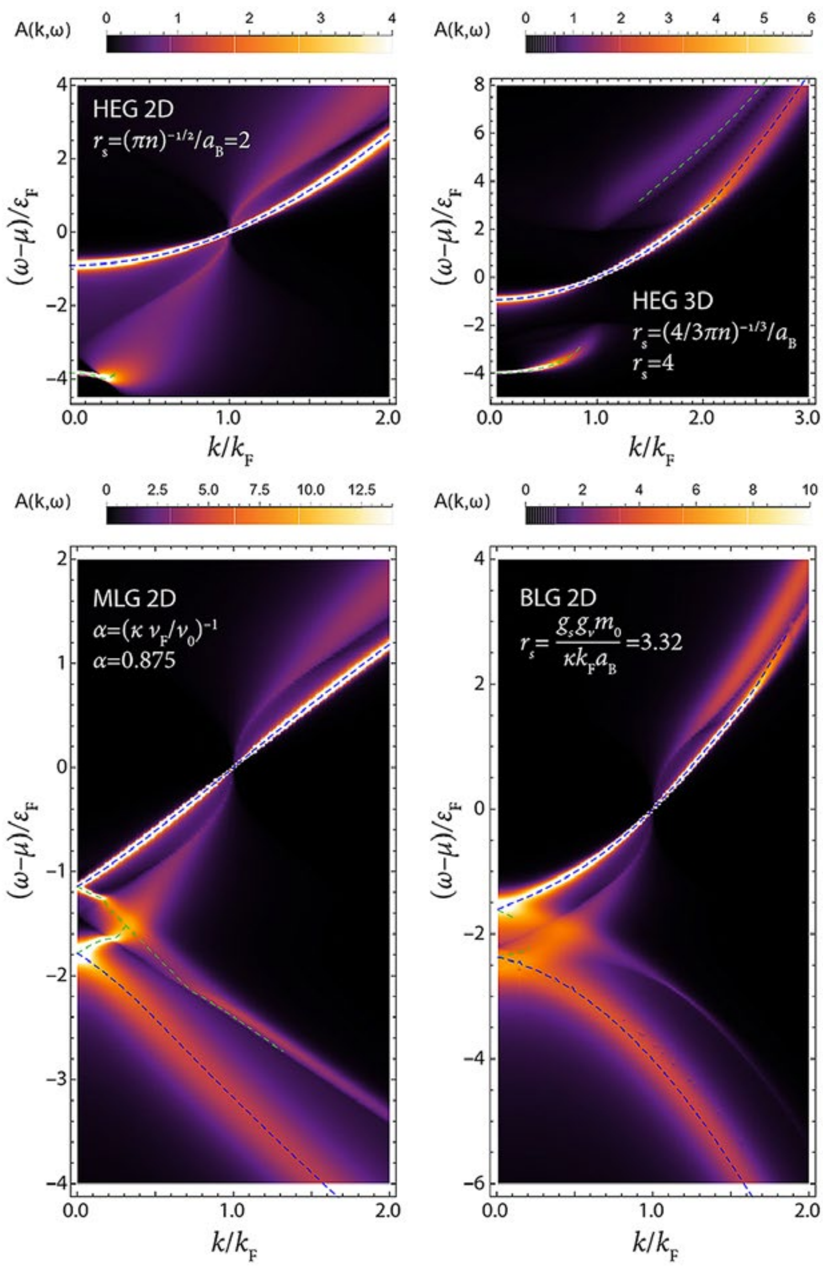
DYNAMICAL VERTICES IN DIAGRAMMATIC MANY-BODY THEORY

Diagrammatic perturbation theory is a powerful tool for the investigation of interacting many-body systems, in which the self-energy operator encodes all the variety of scattering processes.

In the simplest scenario of correlated electrons, described by the GW approximation for the electron self-energy, a particle transfers a part of its energy to neutral excitations. Higher-order (in the screened Coulomb interaction W) self-energy diagrams lead to improved electron spectral functions by taking more complicated scattering channels into account and by adding corrections to lower order self-energy terms. However, they also may lead to unphysical negative spectral functions. The resolution of this difficulty has been demonstrated in our previous works in which we developed a completely new formalism to deal with this issue. The main idea is to represent the self-energy operator in a Fermi golden rule form which leads to a manifestly positive definite spectral function and allows for a very efficient numerical algorithm. Initially our method was applied to the three-dimensional electron gas, which is a paradigmatic system. Recently [1] we systematically extended the method to two dimensions including realistic systems such as monolayer and bilayer graphene. We focused on one of the most important vertex function effects involving the exchange of two particles in the final state. We demonstrated that it should be evaluated with the proper screening and discussed its influence on the quasiparticle properties.

QUANTUM MANY-BODY THEORY BEYOND THE BORN-OPPENHEIMER APPROXIMATION

The description of interactions between electrons and atomic nuclei in molecular and solids state physics is commonly treated in the Born-Oppenheimer approximation in which the atomic nuclei do not have any dynamical degrees of freedom and are effectively treated as having infinite mass. We extended the many-body formalism to incorporate quantum nuclear motion by introduction of a many-body body-fixed frame and a corresponding transformation of the many-body Hamiltonian. Coupled equations between electron-electron, electron-nuclear and nuclear-nuclear propagators are derived [2] using Schwinger's source technique and the emergence of non-Born-Oppenheimer effects, such as those of Coriolis form, are analyzed in detail and approximation schemes are developed to evaluate these contributions using perturbation theory.



↑ Figure 1. Spectral functions in the momentum-energy plane for the two- and three-dimensional electron gas (upper panels) as well as for one monolayer and bilayer graphene from diagrammatic perturbation theory [1].

Selected publications

[1] Y.Pavlyukh, G.Stefanucci and R. van Leeuwen, Dynamically screened vertex corrections to GW, Phys. Rev. B**102**, 045121 (2020)

[2] V.Härkönen, R.van Leeuwen and E.K.U.Gross, Many-body Green's function theory for electrons and nuclei beyond the Born-Oppenheimer approximation, Phys. Rev. B**101**, 235153 (2020)

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.

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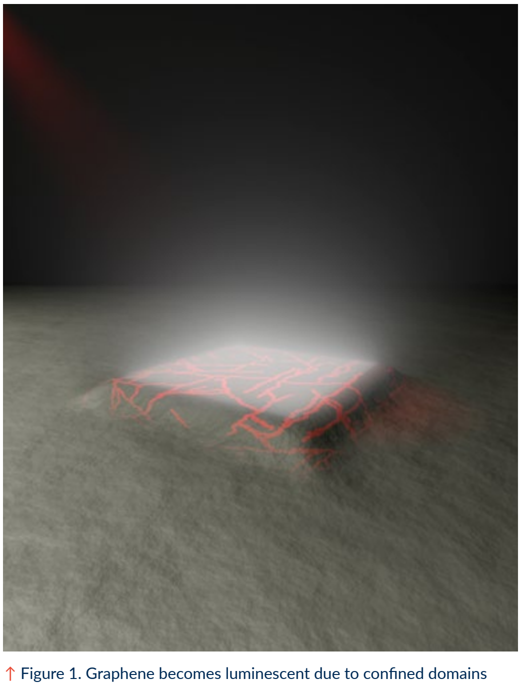

↑ Figure 1. Graphene becomes luminescent due to confined domains created by line defects. Visualization: Otto Koskinen.

MAKING GRAPHENE LUMINESCENT

Graphene is not intrinsically luminescent due to a lack of band gap, and methods for its creation are tricky for device fabrication. In collaboration with the experimentalists at the chemistry department, we employed a direct laser writing method on graphene to create luminescent patterns.[1] Raman spectroscopy analysis revealed that the laser writing induces point defects that grow into line defects upon prolonged irradiation. Guided by these experimental findings, we developed a phenomenological model that explains the luminescence in terms of small confinement domains formed by line defects. This mechanism for luminescence resembles conceptually the one in graphene quantum dots (Figure 1).

TWO-DIMENSIONAL ELEMENTAL METALS FROM BINARY METAL ALLOYS

During 2020, we continued our work on elemental two-dimensional (2D) metals, a research field that has gained significant momentum since our pioneering contributions.[2] Inspired by recent experiments, we investigated an approach in which 2D metals are formed by electron irradiation of binary metals. Our simulations suggest that the approach could also be used to form Au monolayers from the Au–Cu alloy and Pt monolayers from Pt–Cu, Pt–Ni, and Pt–Pd alloys.[3] Again, 2D metals showed stability and resilience far beyond what was expected.

Selected publications

[1] V.-M. Hiltunen, P. Koskinen, K. K. Mentel, J. Manninen, P. Myllyperkiö, A. Johansson, & M. Pettersson. Making Graphene Luminescent by Direct Laser Writing. *The Journal of Physical Chemistry C*, ***124***, 8371 (2020)

[2] J. Nevalaita and P. Koskinen (2018). Atlas for the properties of elemental two-dimensional metals. *Physical Review B*, ***97***, 035411 (2018)

[3] J. Nevalaita and P. Koskinen. Free-standing 2D metals from binary metal alloys Free-standing 2D metals from binary metal alloys. *AIP Advances*, ***10***, 065327 (2020)

SUPERCONDUCTING SPINTRONICS

Academy research fellow Mihail Silaev

We study transport and dynamical properties of correlated electron systems and their interaction with quantum fields such as photons and magnons. We have started in 2016 supported by the Academy of Finland project focused on the physics of non-equilibrium spin states in superconducting materials. In the future we plan to study topological states of matter and exotic dynamical states in hybrid quantum systems. At the moment the group consists of PhD student Risto Ojajärvi and postdoc Alexei Shorokhov.

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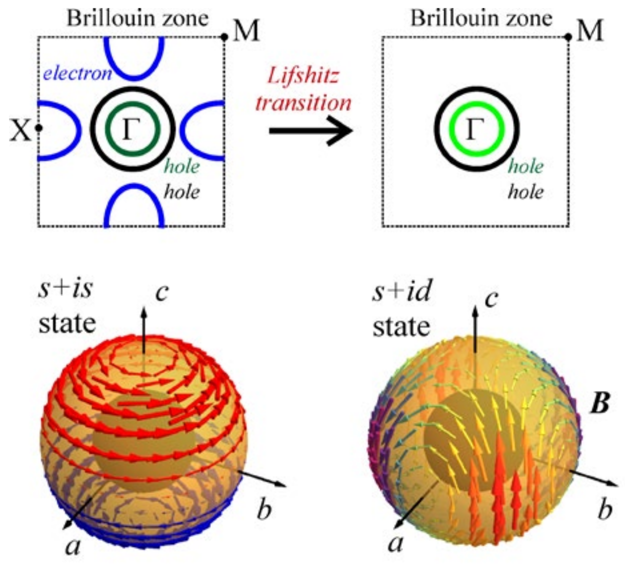


↑ Figure 1. (Upper panel) Schematic structure of the Brillouin zone in multiband superconductor $Ba_{1-x}K_xFe_2As_2$. (Lower panel) Spontaneous magnetic field generated around spherically symmetric inhomogeneity in superconductors with broken time-reversal symmetry.

PREDICTION AND OBSERVATION OF A NOVEL STATE WITH BROKEN TIME REVERSAL SYMMETRY IN MULTIBAND SUPERCONDUCTORS.

We have predicted [1,2] the s+is superconducting state with spontaneous magnetic near inhomogeneities as shown in the Figure. Recently such state has been observed by muon spin relaxation measurements inside the superconducting state of metallic compounds $Ba_{1-x}K_xFe_2As_2$ within a certain range of K doping level [3]. We have provided theoretical support and interpretation of experimental results. These experimental findings together with other data show the connection between s+is state and a change in the topology of the Fermi surface (Lifshitz transition) as illustrated in the Figure.

PROBING ANDREEV BOUND STATES IN SUPERCONDUCTORS WITH THE HELP OF SPIN PUMPING

This work [4,5] demonstrates how Andreev bound states can enhance the spin pumping efficiency in ferromagnetic/superconductor bilayer. Bound states in superconducting hybrid structures are central for the further development of quantum information technologies. Previously such states have been probed by tunneling spectroscopy. The present work shows that they modify also dynamical spin responses. In accordance with recent experimental results Andreev bound states are shown to provide significant enhancement of spin pumping efficiency and Gilbert damping.

Selected publications

[1] Garaud, Julien, Mihail Silaev, and Egor Babaev, Phys. Rev. Lett., 116 097002 (2016).

[2] Vadimov, V. L., and M. A. Silaev, Phys. Rev. B 104504, 98 (2018).

[3] V. Grinenko, et al, Nature Physics, 16, 789 (2020)

[4] M. A. Silaev, Phys. Rev. B 102, 180502(R) (2020)

[5] M. A. Silaev, Phys. Rev. B 102, 144521 (2020)

ACCELERATOR LABORATORY

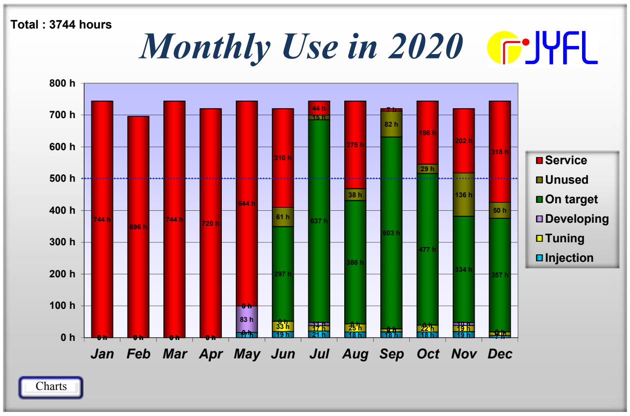
Professor Paul Greenlees
Head of Accelerator Laboratory

In January 2020, the Accelerator Laboratory (JYFL-ACCLAB) was in the middle of its first extended shutdown in thirty years. The shutdown was necessary in order to complete the overhaul of the operational control system of the facility. The demanding work was led by Operations Manager Arto Lassila and his excellent hard-working team: Markus Liimatainen, Kalle Salminen and Olli Leiviskä, backed up by the staff of the electronic and mechanical workshop and our cyclotron operators. In addition to the control system upgrade, the opportunity was taken to perform other maintenance tasks, including checking and re-alignment of the beam-lines, cleaning and maintenance of the inner parts and RF of the cyclotron, installation of parts to aid modification of the cyclotron central region and repair of the inflector changing mechanism. In March, JYFL-ACCLAB played host to budding young scientists – high school students who had participated in the "Kiihdytin Hiukkasen" competition and granted the right to carry out an experiment using the laboratory accelerators and infrastructure. In parallel, staff of the laboratory were preparing for the re-start of operations and eagerly awaiting the possibility to carry out experiments.

Of course, the staff would have to wait a considerable time longer, as the spreading and effects of the SARS-CoV-2 virus became apparent and Finland and the University began to apply restrictions on travel and events on the 11th March. On Friday 13th the conditions surrounding the thesis defence of Joshua Hilton, the first graduate of the JYFL-University of Liverpool Joint Doctoral Program, had to be hastily re-organised with online participation. Over the following weekend, due to a suspected infection, the whole Ylistö campus was rapidly moved to remote working and what turned out to be a much longer period of disruption due to COVID-19 began. Lockdown conditions and restrictions on travelling meant that all scheduled experiments had to be cancelled and only a skeleton crew of critical technical staff were allowed on site. During the lockdown, only work deemed as critical to maintaining operations or safety was allowed. An exception was granted to perform an irradiation for one of our commercial customers, as it was desperately required in order to produce membranes employed in restricting the spread of COVID-19. The irradiation was carried out under extreme quarantine conditions and its' success due to the considerable efforts of Heikki Kettunen to make the arrangements.

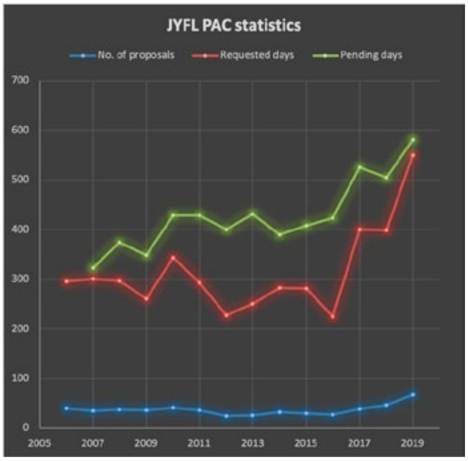
Over the summer, restrictions were slowly lifted and it became possible to start running experiments and performing irradiations for commercial customers once again, including plans for hosting visitors from abroad to participate**.** The resurgence of the pandemic in the Autumn resulted in the re-introduction of travel restrictions and the majority of scheduled experiments were led by local spokespersons and executed using local staff with very few foreign visitors. The acute needs of our commercial customers were highlighted by the fact that they were willing to go into quarantine for up to fourteen days in advance of carrying out irradiations of a few days at the RADEF facility.

Despite the extended shutdown and the effects of COVID-19, the K130 cyclotron provided a total of 3744 beam time hours provided in over 30 different runs for research experiments and periods of irradiation for industrial applications at the RADEF facility (see Figure 1).



↑ Figure 1: Use of the K130 cyclotron by month in 2020.

Demand for beam time from the K130 cyclotron remains at an unprecedentedly high level (see Figure 2). In 2020 a total of 37 proposals were submitted to the Program Advisory Committee requesting 345 days of beam time for research.



↑ Figure 2: Statistics of the number of proposals submitted to the JYFL-ACCLAB PAC since 2006.

Funding from the Academy of Finland led to some changes in titles and the possibility to continue actions related to the latest University profiling action (Profi5). An Academy of Finland Research Fellowship was awarded to Mikko Laitinen and a new University Tenure Track position was opened with focus on the complementary research program to be carried out at the future FAIR facility. As a result, Tuomas Grahn was named as an Associate Professor to fill the position. With a view to the future and to ensure continued expertise in cyclotron and accelerator physics a Staff Scientist position was opened which was filled by Taneli Kalvas.

In 2020, there was once again a retirement of a significant figure who has been involved in the activities of the laboratory in one way or another throughout its' history. Chief Engineer Jaana Kumpulainen retired at the end of August, after serving as the Radiation Safety Officer since the beginning of 2007. Jaana started her physics studies at the University in September 1975 and defended her PhD Thesis in 1990. Before starting as the Radiation Safety Officer at JYFL, she worked for MAP Medical Technologies where she was in charge of radioisotope production with irradiations carried out at JYFL-ACCLAB. Being a nuclear physicist and having experience in radioisotopes, Jaana was a highly appreciated expert in radiation safety and hence had several duties regarding radiation safety such as education and preparation of the recently adopted new Radiation Act.

Finally, on 11th December, an early Christmas present was received from the Academy of Finland – our application to be considered as one of the Research Infrastructures on the Finnish Research Infrastructure (FIRI) Roadmap was successful. JYFL-ACCLAB was selected as one of 29 significant facilities for the FIRI Roadmap for 2021–2024.

↑ Figure 3: Taneli Kalvas installing the new central region of the K130 cyclotron.

↑ Figure 4: Jaana Kumpulainen checking the residual activity in an electron accelerator used for radiation therapy.

NUCLEAR SPECTROSCOPY

Professor Paul Greenlees
Associate Professor Tuomas Grahn
Staff Scientist Jan Sarén
Doctoral student Henna Joukainen
Senior Researcher Janne Pakarinen

The main activities of the Nuclear Spectroscopy group are related to using in-beam gamma-ray and electron as well as decay-spectroscopic methods to examine the microscopic structure of the nucleus through studies of exotic nuclei, mainly along the proton drip line and in the region of heavy elements. The group is also active in international collaborations such as MINIBALL, IDS and ISS at ISOLDE, CERN, in the AGATA collaboration to build a gamma-ray tracking array and in the SUPER-FRS and HISPEC/DESPEC collaborations which form part of the NuSTAR pillar of FAIR in Germany. In 2020, the group continued to focus on experimental in-beam spectroscopy campaign with the JUROGAM 3 array of germanium detectors at the MARA separator. Despite the disruption and enforced breaks in activity due to the shutdown and COVID-19, a total of 63 days of beam time were distributed to 7 separate experiments. The group members were co- authors in 33 peer-reviewed journal publications and 6 conference proceedings.

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

↑ Figure 1: The Nuclear Spectroscopy Group enjoying a socially-distanced group meeting

In the first months of 2020, during the extended shutdown to upgrade the control system of the Accelerator Laboratory, our group members participated in experiments at Legnaro in Italy and at GSI-FAIR in Darmstadt, Germany on the cusp of the COVID-19 crisis. Indeed, soon afterward it became clear that both of these areas had become centres for infection and our researchers managed to return from travels just as the borders to Finland closed behind them. On Friday 13th March, our Doctoral Student Joshua Hilton was due to defend his thesis "*Decays of new nuclides ^{169}Au, ^{170}Hg, ^{165}Pt and the ground state of ^{165}Ir discovered using MARA*" with opponent Dr. Jadambaa Khuyagbaatar from the Helmholtz-Institute Mainz and GSI Helmholtz Centre for Heavy Ion Research, Germany. Whilst the opponent was en-route, entry restrictions for visitors were imposed and led to some hectic re-arrangements and organization for the supervisor and chair of the defence, Juha Uusitalo. Joshua is the first graduate from the Joint Doctoral Degree Program with the University of Liverpool.

RESEARCH ACTIVITIES

As stated above, the main focus of research by the group was on the experiments carried out at the MARA vacuum-mode separator coupled to the array of germanium detectors known as JUROGAM-3. Since being commissioned a few years ago, MARA has demonstrated that it is a device with performance comparable to the best vacuum-mode spectrometers of this type in the world. The program at MARA has the study of nuclei with approximately equal numbers of neutrons (N) and protons (Z) as one of its' central tenets. These so-called N=Z nuclei are excellent laboratories to study isospin symmetry and symmetry breaking effects. The strong overlap of proton and neutron wavefunctions also gives the possibility to observe new, unexpected phenomena and the development of collectivity. A further, traditional theme of the work of the Nuclear Spectroscopy has been the study of nuclei at and beyond the proton drip line, where the spontaneous emission of protons from the nucleus becomes a viable decay mode.

The experiments carried out in the latter part of 2020 have followed these themes. Following a brief test in June of a new scintillator detector for beta particles used in Recoil-Beta Tagging (RBT) experiments (see below), the first full production experiment of the year was to study isospin symmetry breaking in the mass 62 isobaric triplet. The experiment focused on ^{62}Ge and ^{62}Ga and a relatively high level of statistics was obtained for ^{62}Ga and candidate peaks for the first observation of states in ^{62}Ge were observed.

A similar experiment to study isospin symmetry was carried out in the mass 66 isobaric triplet. The experiment was a follow-up to previous studies carried out at RITU and focused on ^{66}Se and ^{66}As. These data allowed for a proof-of-principle of the technique of Double-Beta Tagging (DBT) to be carried out and resulted in the observation of new high-spin structure in ^{66}As.

In order to better understand the contributions of different nuclear excitations to the differences of energies of states in mirror nuclei, an experiment was carried out to study nuclei with mass 43. Initial analysis is promising suggests that the high-spin states of interest in ^{43}Sc and ^{43}Ti were populated with sufficient intensity.

On theme of nuclear shapes and development of collectivity, an experiment to study octupole correlations in the very neutron-deficient nucleus ^{110}Xe was performed. A very high level of statistics was obtained, along with data on several other nuclei such as $^{106\text{-}109}$Te and ^{109,110}I.

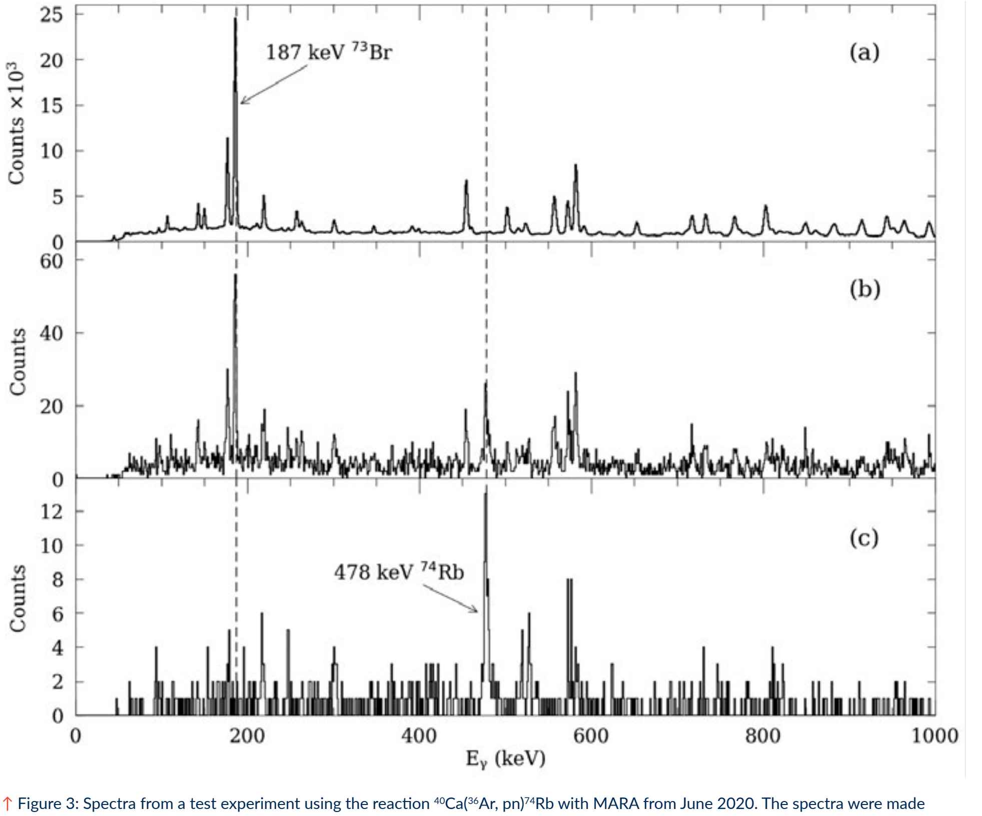
Moving to heavier nuclei, a search was made for a new proton-emitting isotope ^{149}Lu, which is predicted to have an oblate deformation. The final experiment of the year was dedicated to investigation of ^{211}Ac, with a view to searching for possible intruder and isomeric states. Analysis from all experiments is ongoing and will be published in due course.

The intensive program of running experiments has been done solely with the efforts of the local groups, as visitors have not been able to participate due to the restrictive nature of quarantine rules. This has, however, led to closer collaboration between the local groups with participation in each other's experiments and better understanding of the work of each group.

TECHNICAL DEVELOPMENTS

A new position-sensitive beta detector for the focal plane of the MARA vacuum-mode separator was built and tested in 2020. The new detector was designed to efficiently detect beta particles at the focal plane of MARA for better separation of events relating to certain nuclei of interest, usually those residing near the N=Z line for which the Recoil-Beta Tagging (RBT) technique is applicable. The detector is an array of plastic scintillator bars with the light collected by Silicon Photomultipliers (SiPMs), making it compact: the volume taken by the scintillators is only 14 x 8 x 3 cm, and neither the SiPMs, surrounding frame nor cables take up much space (see figure 2). Initial tests of the detector performance have proven that it has sufficient energy resolution to separate high-energy beta particles and good position sensitivity. The detector has already been used in several recoil-beta tagging experiments. In figure 2, it can be seen that use of the detector enhances the sensitivity to select ^{74}Rb from a background of beta-decaying nuclei. The detector was the subject of the MSc thesis of Henna Joukainen, who recently joined the group as a Doctoral researcher.

↑ Figure 2: Henna Joukainen installing the scintillator detector in the focal plane vacuum chamber of MARA.



↑ Figure 3: Spectra from a test experiment using the reaction ^{40}Ca(^{36}Ar, pn)^{74}Rb with MARA from June 2020. The spectra were made requiring (a) a recoil gate, (b) recoil gate and a fast beta decay in DSSD and (c), recoil gate, a fast beta decay in DSSD and a high-energy beta in the new beta detector.

← Figure 4: Photograph of the newly upgraded focal plane detection system at RITU.

In parallel to the campaign of experiments and developments at MARA, the focal plane detection system of the gas-filled recoil separator RITU has also been upgraded. The focal plane at RITU formerly hosted the GREAT spectrometer (built by colleagues from the UK), but has now been modified to incorporate a system very similar to that used at MARA. In this way, there is greater redundancy of parts and switching from one experimental set-up to another is made more simple. The majority of the work at RITU has been carried out by Jussi Louko, who is also a Doctoral researcher in the group.

EXTERNAL RESEARCH

The group participated in the 2020 Phase-I experimental campaign of FAIR. The main theme was to provide data relevant for astrophysical nucleosynthesis processes. This was done through measurements of atomic masses, radioactive beta-decay half-lives and spectroscopy of excited states in atomic nuclei. Experiments were dedicated to isotopes below ^{100}Sn and around neutron number *N*=126. These regions represent two current topics in nuclear physics, addressing the structure of self-conjugate (*N*=*Z*) nuclei and measuring nuclear data relevant for *r*-process nucleosynthesis (*N*=126). While the data analysis is still ongoing, it is clear that valuable data such as newly identified isotopes, their masses and decay properties will be extracted.

Another highlight of 2020 was the publication of the first experimental physics result obtained using the SPEDE spectrometer developed in collaboration between the University of Jyväskylä and University of Liverpool. The discovery of a new alpha-emitting state enabled the location of several excited states in the ^{186}Tl nucleus to be determined. These findings also shed light on the role of the proton $d_{3/2}$ shell in the region where shape coexistence is most prominent.

Selected publications

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Pakarinen, J.; Ojala, J.; Ruotsalainen, P.; Tann, H.; Badran, H.; Calverley, T.; Hilton, J.; Grahn, T.; Greenlees, P. T.; Hytönen, M.; Illana, A.; Kauppinen, A.; Luoma, M.; Papadakis, P. et al. (2020). The JUROGAM 3 spectrometer. European Physical Journal A, 56 (5), 149. DOI: 10.1140/epja/s10050-020-00144-6 *Open Access*

Barber, L.; Heery, J.; Cullen, D.M.; Singh, B.S. Nara; Herzberg, R.D.; Müller-Gatermann, C.; Beeton, G.; Bowry, M.; Dewald, A.; Grahn, T.; Greenlees, P.T.; Illana, A.; Julin, R.; Juutinen, S. et al. (2020). A charge plunger device to measure the lifetimes of excited nuclear states where transitions are dominated by internal conversion. Nuclear Instruments and Methods in Physics Research Section A: Accelerators Spectrometers Detectors and Associated Equipment, 979, 164454. DOI: 10.1016/j.nima.2020.164454 *Open Access*

EXOTIC NUCLEI AND BEAMS

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

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

https://www.jyu.fi/igisol

ON-GOING PROJECTS AND RESEARCH ACTIVITIES

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. In SANDA (Supplying Accurate Nuclear Data for Energy and Non-energy Applications) Joint Research Activity, we have two tasks: to develop and verify a fission yield measurement technique based on the PI-ICR method at JYFLTRAP, and to design a large gas cell for IGISOL with electric field guidance. The ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning) transnational access project will provide support for external user experiments at IGISOL. 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. Ruben de Groote's RAPTOR, "RIS And Purification Traps for Optimized spectRoscopy" Marie Curie Individual Fellowship aims

↑ Figure 1. IGISOL group members in one of the many remote Zoom meetings.

to realize a small-footprint CRIS beamline which will connect to the JYFLTRAP beamline. In 2020, the Marie Curie Innovative Training Network LISA (Laser Ionisation and Spectroscopy of Actinides) commenced, with one Ph.D. funded researcher, Andrea Raggio, joining our team. Academy Research Fellow project of Tommi Eronen searches for potential beta decay candidates to be used for neutrino mass searches. Our group is also leading the development and exploitation of the first phase of MARA-LEB at JYFL-ACCLAB, with an ongoing academy project led by Iain Moore.

In addition to the experimental programme at IGISOL, we contribute to the FAIR project. In 2020, members of our team participated remotely in Phase-0 experiments at FAIR/GSI due. The experiments covered a broad spectrum of physics, including mass measurements and decay studies of heavy neutron-rich nuclei in the *N*=126 region

DEVELOPMENTS

Despite the COVID-19 pandemic, developments in 2020 continued.

First isobaric mass separation with the multi-reflection time-of-flight separator

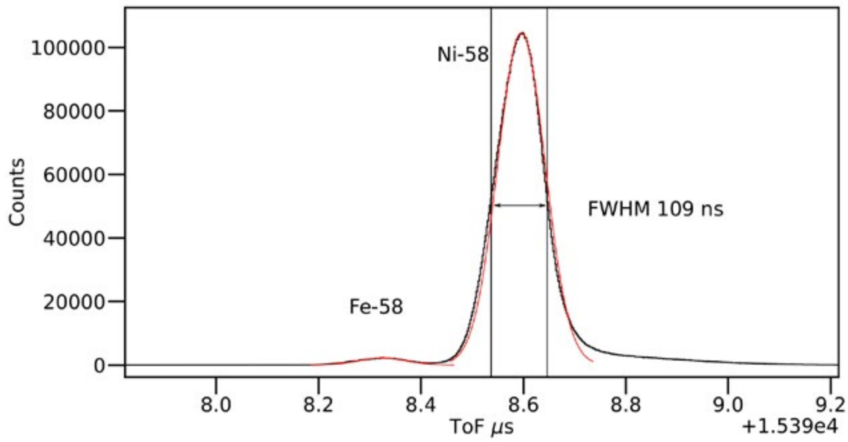
The commissioning of the multi-reflection time-of-flight separator took a step closer to the application of the device for on-line experiments. In the recent milestone, stable Ni-58 and Fe-58 isotopes produced simultaneously in an electrical discharge ion source were mass separated with a mass resolving power M/ΔM of 70,000 (See Fig. 2). Such resolving power is already sufficient for separating or measuring the masses of most of the exotic isotopes. The next phase in the commissioning is to transfer the ions to the downstream Penning traps and improve the overall efficiency.

RAPTOR

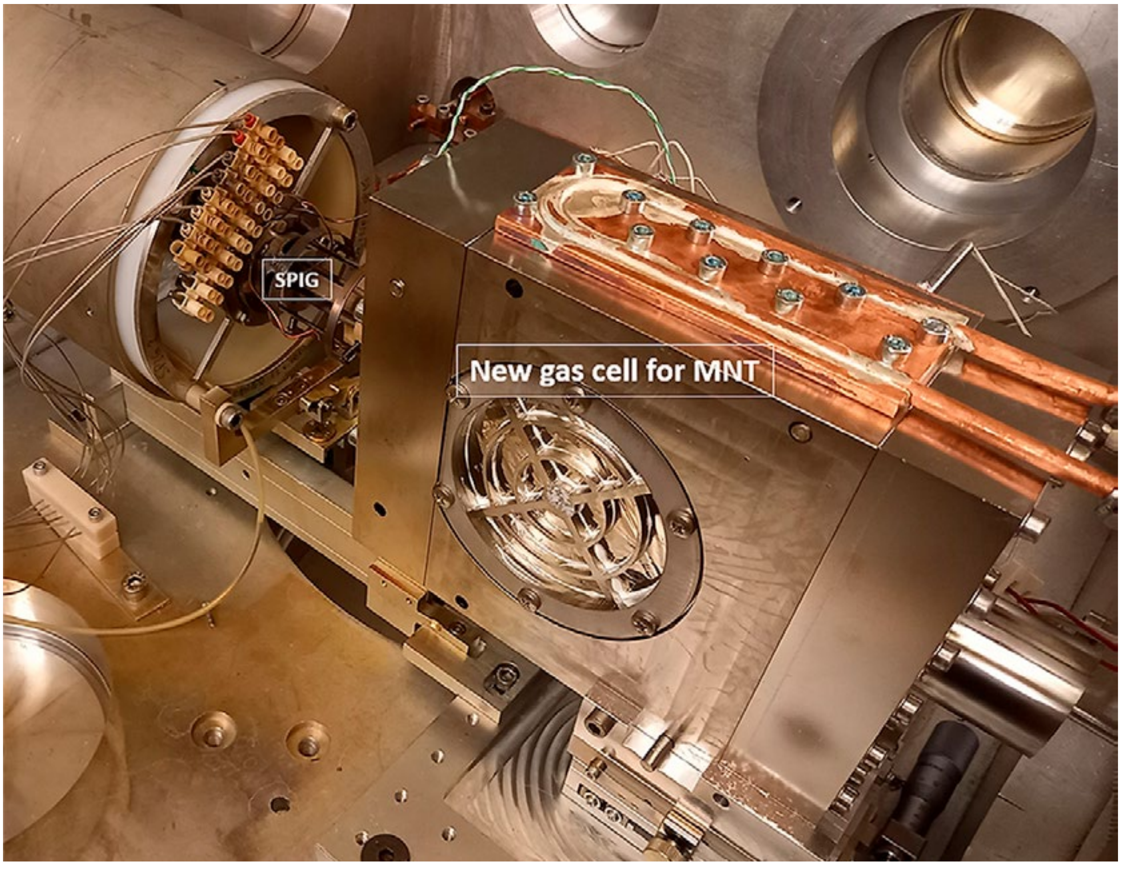
The construction of a new beamline in the IGISOL laboratory, as part of a Marie Skłodowska-Curie Fellowship, was completed on schedule in late 2020. This new apparatus will be used for medium-resolution, high-efficiency collinear resonance ionization spectroscopy experiments. Located inside a Faraday cage, the entire apparatus can be placed at a high-voltage, enabling the use of beam energies between 1 and 10 keV. The use of these slower beams allows for a more compact design, in turn enabling the injection of laser-separated ion beams into the JYFLTRAP double-Penning trap mass spectrometer for ultra-low background conditions. Over the coming months, this device will be commissioned and characterized using suitable stable beams. A proposal targeting short-lived isomeric states in bismuth, with lifetimes below 10 ms, was already accepted by the Physics Advisory Committee, and will thus be the focus of the first radioactive ion beam experiments using this new beamline.

Multinucleon-transfer reaction ion guide

A new ion-guide gas cell for multinucleon-transfer (MNT) reactions has been designed and manufactured in the ERC CoG MAIDEN project (see Fig. 3). The first tests with the new gas cell were performed in November 2020, and the initial results look promising. Overall ion extraction and transport efficiencies were determined for helium gas flow with a ^{223}Ra alpha recoil source and yielded efficiencies up to around 13%. Online tests with ^{136}Xe beam on a ^{208}Pb target were also performed. In the test run, the beam was stopped before the gas cell. More online tests will be done in 2021 with a configuration where the primary beam goes through the gas cell in a narrow tube and is stopped after the gas cell. The use of MNT reactions enables studies of neutron-rich nuclei beyond the fission fragment region at IGISOL.



↑ Figure 2. Separation of stable $^{58}Ni^{+}$ and $^{58}Fe^{+}$ ions with a mass resolving power of 70,000.



↑ Figure 3. New MNT gas cell designed for multinucleon-transfer reactions at IGISOL.

RESEARCH HIGHLIGHTS

In the following, selected experimental and publication highlights from 2020 are summarized.

Collinear laser spectroscopy of radioactive palladium isotopes

Continuing the successful campaign of collinear laser spectroscopy of palladium isotopes (Z=46) in which the neutron-rich isotopes were highlighted last year, we continued this work on neutron-deficient isotopes. Prior to these studies, no nuclear charge radii had been measured for any radioactive Pd isotopes. Now, the dataset spans from A=98 to A=118. This new data will be used to track the evolution of nuclear shapes between the spherical Sn isotopes (Z=50) and the well-deformed Zr isotopes (Z=40). Furthermore, the results are expected to form an important benchmark for theoretical calculations within e.g. the Fayans DFT framework, performed in-house by Dr. Markus Kortalainen. Two publications are currently being prepared.

Offline developments towards on-line measurements on vanadium, chromium and cobalt

Taking advantage of the access to offline beams, extensive spectroscopic scheme development work was performed on Ti, V, Cr and Co. One of the key motivations for future online experiments on the proton-rich isotopes of these elements is to investigate in detail the intricate trends in the mean-squared charge radii in the calcium region. For chromium, very efficient neutralization was attained, and optimal optical transitions were found. A proposal to study $^{48\text{-}55}$Cr was accepted by the Physics Advisory Committee. For Co, frequency-quadrupling of continuous-wave laser light was realized for the first time in the laboratory, and first hyperfine spectra of Co was obtained. Additional offline work on Co, as well as V, is planned in the coming months, in preparation for future proposals.

Actinide studies

In 2020 we published our series of measurements on thorium dispensers which have the potential to act as sources for future collinear laser spectroscopy experiments [Pohjalainen *et al*, Nucl. Instrum. and Meth. B (2020)]. This work demonstrated the importance of understanding the complexities associated with resonance laser excitation on actinides in gaseous environments. Online, we continued our investigation of light actinide isotope production via fusion-evaporation reactions on ^{232}Th with a successful decay spectroscopy experiment in July 2020. Recoils as exotic as ^{224}Pa were detected, up to 9 evaporated neutrons emitted in the reaction.

Beta decay Q-value measurements for neutrino studies

Several ground-to-excited state beta and electron-capture transitions have the potential to become the next probe for the neutrino mass. These decays should have a decay energy (Q-value) on the order of 1 keV or less so that their decay spectrum shape would be easy to describe and the shape distortion manifested by the finite neutrino mass susceptible for study. The first step is to confirm that the Q-values are positive, requiring sub-keV precision of the excitation energy and the ground-state-to-ground-state decay Q-value. The former is usually known to sufficient precision while the latter are poorly known and often lack a direct measurement. The ^{135}Cs ground-state-to-ground-state Q-value was recently measured and improved by a factor of three [de Roubin *et al.*, Physical Review Letters (2020)]. The decay was found to be energetically suitable and the estimated branching ratio at the level of 10^{-5}, similar to the beta decay of ^{115}In, which currently has the lowest Q-value of any beta decay.

In 2020, we continued the search for potential candidates by measuring the Q-values of several cases including a number of electron capture, beta+ and beta- candidates ranging from ^{72}As to ^{161}Ho. With the expertise of the in-house nuclear theory group of Prof. Jouni Suhonen, we are able to estimate the partial half-lives of these transitions and shed light on the applicability of these decays to neutrino mass determination.

Mass measurements of neutron-rich nuclei

The mass measurement programme on neutron-rich nuclei for nuclear structure and the astrophysical rapid neutron capture process, the r process, continued in 2020. The measurements done in 2019 in the Rh, Ru and Ag isotopic chains were extended to lighter refractory elements, and in particular to their most exotic nuclides, such as ^{104}Y, ^{106}Zr, ^{109}Nb, and ^{111,112}Mo, in 2020. The application of the PI-ICR technique enabled the measurements of low-lying isomeric states, for example in the Rh and Ag isotopes. In addition, the three isomeric states in ^{130}In were resolved for the first time using the technique [Nesterenko et *al.*, Physics Letters B (2020)]. JYFLTRAP has measured 22 nuclides in the rare-earth region, 14 of which have been measured for the first time [Vilen et *al.*, Physical Review C (2020)]. The new mass values, when incorporated in the r-process calculations, produce a smoother abundance pattern and better agreement with the observations. In the lighter neutron-rich nuclei, the mass measurements of ^{67}Fe and ^{69,70}Co were reported in 2020 [Canete et al. (2020)]. The results remove ambiguities in the previous mass values and yield a smoother trend on the mass surface, extending it beyond the subshell closure at N = 40. These lighter nuclides are relevant for the formation of the first r-process abundance peak. The recent mass measurements at JYFLTRAP have been summarised in [Kankainen et *al.*, Hyperfine interact. (2020)]. Information on the neutron-rich mass measurements and nuclear astrophysics research can be found from the ***Nuclear Astrophysics webpage***.

Selected publications

Pohjalainen et al., Nuclear Instruments and Methods B 484, 59 (2020).
[Open Access: JYX]
Gas cell studies of thorium using filament dispensers at IGISOL

A. de Roubin et al., Physical Review Letters 124, 222503 (2020).
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High-Precision Q-Value Measurement Confirms the Potential of 135Cs for Absolute Antineutrino Mass Scale Determination

D.A. Nesterenko et al., Physics Letters B 808, 135642 (2020).
[Open Access: *JYX*]
Three beta-decaying states in 128In and 130In resolved for the first time using Penning-trap techniques

L. Canete et al., Physical Review C 101, 041304(R) (2020).
[Open Access: *JYX*]
Precision mass measurements of 67Fe and 69,70Co: Nuclear structure toward N = 40 and impact on r-process reaction rates

M. Vilén et al., Physical Review C 101, 034312 (2020).
[Open Access: *JYX*]
Exploring the mass surface near the rare-earth abundance peak via precision mass measurements at JYFLTRAP

A. Kankainen et al., Hyperfine Interactions 241, 43 (2020).
[Open Access: *JYX*]
Recent experiments at the JYFLTRAP Penning trap

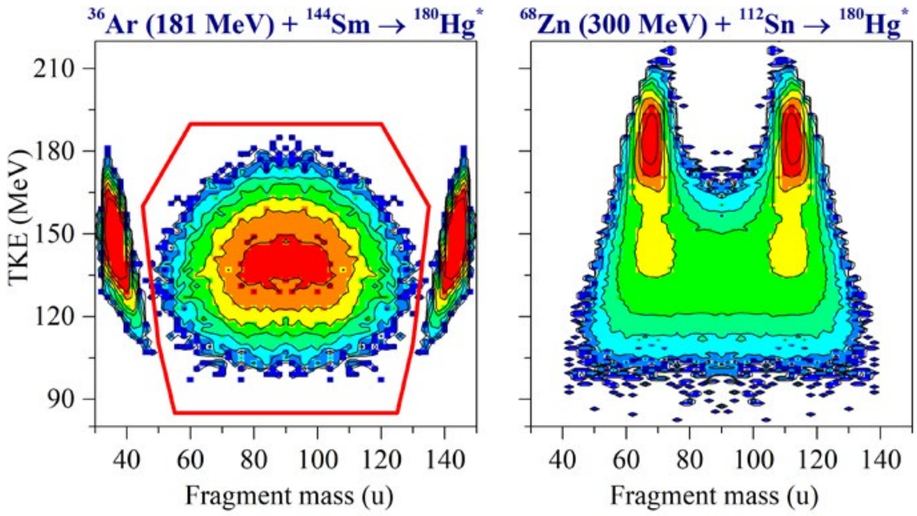
INSTRUMENTS AND METHODS
IN NUCLEAR, PARTICLE, AND ASTROPARTICLE PHYSICS

Senior Researcher Wladyslaw H. Trzaska

One of the most exciting aspects of experimental physics is doing what nobody has done before. Development of 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, and ultra-relativistic cosmic rays. In addition to various spectrometers and devices for the use with cyclotron beams our group continues contributing to the design, construction, and upgrade of the ALICE experiment at CERN, as described in the ALICE chapter of this Annual Report. The status of the Underground Physics is given in the Neutrino and Astroparticle Physics. This section concentrates on Nuclear Reaction studies carried out at the K130 cyclotron and in the other European facilities.

www.jyu.fi/hendes

In 2020, for the first time in the Accelerator Lab's history, there were no Nuclear Reaction (NR) experiments at JYFL as the scheduled cyclotron shutdown was followed immediately by the COVID-19 lockdown. Our experiments at Legniaro, Warsaw, Catania and Dubna had to be postponed for the same reason. While waiting for the end of the pandemic, our efforts focused on data analysis and publications. By the end of the year, we have published eleven NR physics papers and three instrumental articles with several others in the pipeline.



↑ Figure 2. Total Kinetic Energy vs. Fragment Mass distributions for the two reactions leading to ^{180}Hg*.

One of our most interesting recent results is an unexpectedly large contribution of Quasi Fission (QF) measured at JYFL in the reaction ^{68}Zn + ^{112}Sn. The properties and systematics of QF are both interesting and relevant as this is the dominant process hindering the fusion of heavy and super-heavy elements. Traditionally, it is assumed that the ratio between QF and compound nucleus formation is determined by the entrance channel properties such as the mean fissility parameter, the Coulomb parameter, the available energy in the centre of mass, the proximity to the fission barrier, and other. Comparing the results of the ^{68}Zn + ^{112}Sn experiment with the previously measured ^{36}Ar + ^{144}Sm reaction, we have realized that at least one more key parameter must be considered when assessing the creation of a compound nucleus. While both reactions have very similar entrance channel properties, the latter has shown only a small QF contribution. The only significant difference between the two is the entrance-mass asymmetry. To verify our conclusion, we intend to extend our investigation into lower and higher mass asymmetry reactions.

The other fascinating area we explore is a search for neutron and proton halos in light nuclei, including the unstable ^{7}He. Typically, it is considered that only bound neutrons may form a halo. However, there are cases when states' structure in the discrete spectrum is the same below and above the threshold. We have developed two techniques to probe the nucleus' size: the modified diffraction method and the method of asymptotic normalization coefficients. They apply to the ground- and excited states, providing their lifetime is significantly larger than the interaction time. Recently we have concentrated on the isobaric analogue states with isospin T = 1 in the triplet of the A = 14 nuclei: ^{14}C, ^{14}N, and ^{14}O. The signs of a neutron halo in the 1− (6.09 MeV) state of ^{14}C have been known before. We have now confirmed this result and extended the study of the isobaric analogue 1− states into the neighbouring ^{14}N and ^{14}O nuclei. The rms radii for all three mirror nuclei in the studied 1− states are found almost the same: (2.7 ± 0.1) fm for ^{14}C, (2.67 ± 0.07) fm for ^{14}N, and (2.6 ± 0.2) fm for ^{14}O. The enhanced radius is the first indication of the proton halo in the 1− state of ^{14}N.

Selected publications

A.S. Demyanova et al. (2020). Search for Signs of Neutron and Proton Halos in the Isobaric Analog Excited States of A = 14 Nuclei. JETP Letters, 12 (8), 463-470. DOI: 10.1134/s0021364020200011

A.S. Demyanova et al. Possible neutron and proton halo structure in the isobaric analog states of A=12 nuclei. Physical Review C, 102 (5), 054612. DOI: 10.1103/physrevc.102.054612 Open Access

A.S. Demyanova et al. (2020). Halo-like structure in 7He nucleus. In INPC2019: 27th International Nuclear Physics Conference (Journal of Physics: Conference Series, 1643. IOP Publishing Ltd, 012128. DOI: 10.1088/1742-6596/1643/1/012128 Open Access

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

K.V Novikov et al. (2020). Investigation of fusion probabilities in the reactions with 52,54Cr, 64Ni, and 68Zn ions leading to the formation of Z = 120 superheavy composite systems. Physical Review C, 102 (4), 044605. DOI: 10.1103/PhysRevC.102.044605 Open Access

NUCLEAR STRUCTURE AND NUCLEAR PROCESSES

Professor Jouni Suhonen

The nuclear-theory group at JYFL develops nuclear-structure models and applies them to topics of 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 and WIMP-nucleus scattering for direct dark-matter detection. The group is a theory partner in many large international experimental collaborations and research laboratories. It pursues also intense collaboration with the local Global Propeties of Nuclei and JYFLTRAP groups, as well as some external theory partners.

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

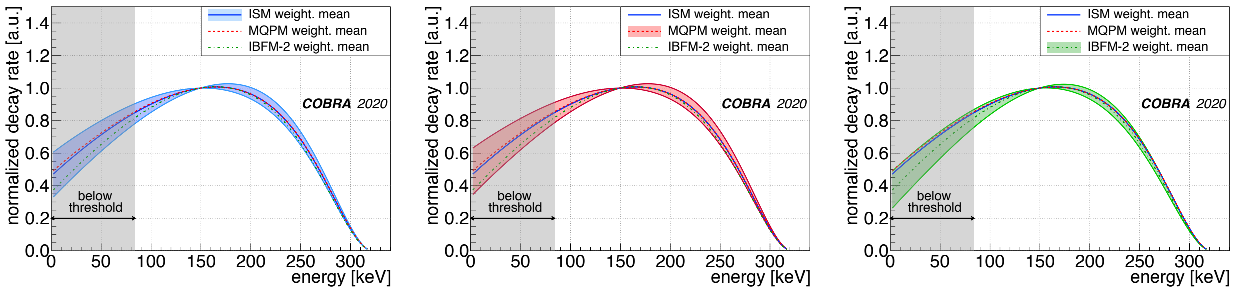
WEAK AXIAL COUPLING AND BETA-DECAY SPECTRAL SHAPES

Neutrinoless double beta (0v-DBD) decay of atomic nuclei is a second-order weak process with a potentially strong impact on the physics beyond the standard model of electro-weak interactions [1]. This process relates to Majorana mass of neutrinos, lepton-number conservation, charge(-conjugation)-parity (CP) violation in the lepton sector, etc. [1]. This process is under a vigorous experimental investigation, pursued by a plethora of large on-going and future underground experiments [1]. Thus far, no experimental evidence of this decay mode has been achieved.

Detection of 0v-DBD would give access to the absolute mass scale of neutrinos, the relative mass scale having been pinned down by the neutrino-oscillation experiments [1]. The measured half-life can be converted to neutrino mass through the nuclear matrix elements (NMEs), condensing the nuclear-structure effects on the decay process. The conversion to neutrino mass depends strongly on the value of the weak axial coupling g-A, the value of which in atomic nuclei is renormalized and largely uncertain. In the nuclear-structure calculations usually an effective value of this coupling, instead of the free-neutron value of 1.27, has been adopted.

Traditionally, the effective value of g-A has been determined from nuclear beta decays by comparing the computed half-life with the measured one. This procedure can be coined the “half-life method”. A complementary method for determining this effective value, the so-called spectrum-shape method (SSM) has been introduced and used recently in [2]. This method relies on the sensitivity of the spectral shape of the emitted electrons to the value of the axial coupling in a given beta-decay transition. This sensitivity can only be realized for the so-called forbidden non-unique (more than one involved NME) beta decays, and since the conception of the SSM suitable candidates for experimental analyses have actively been searched for, most recently in [2].

In addition to the SSM, the electron spectral shapes of forbidden beta transitions play a key role for the so-called reactor-antineutrino anomaly [3] which is tied to the existence of the hypothetical sterile neutrinos. The spectral shapes play a role also for the potential



↑ Figure 1. Number of emitted electrons (normalized decay rate in arbitrary units) as a function of the electron kinetic energy. Ranges of beta spectra computed with the ISM (left panel), the MQPM (middle panel) and the IBFM-2 (right panel) are indicated by the shaded regions. The spectral shapes corresponding to the central values of the axial coupling for the other two nuclear models are also shown by the solid and dash-dotted curves. The light-shaded region on the left is the electron-energy region below the detector threshold.

neutrino-mass detectors with ultra-low decay energies, like in the case of the beta decay of Cs-135, where a joint study with the local IGISOL-JYFLTRAP group was performed [4]. Forbidden spectral shapes feature also as backgrounds of large liquid-xenon-based neutrino and dark-matter detectors, like the XENON1T, which recently measured a potential signal of solar axions or axion-like dark matter. These backgrounds have recently been analyzed in [5].

Tests of the computed electron spectral shapes of non-unique forbidden beta decays against measured ones are called for. One test case is the beta decay of Xe-137 for which the spectral shape computed by our theory group could successfully be compared with that measured by the EXO-200 double beta collaboration in a joint publication [6]. Another example is the decay of Cd-113, well suitable for the SSM analysis, where our computed spectral shapes for different values of the axial coupling could be compared against the one measured by the COBRA collaboration in a joint publication [7]. A further study of this sort has been conducted using a revised, CVC-inspired (CVC signifies conserved vector current) enhancement of the SSM. In this work, as also in [7], the spectral shapes computed by three different nuclear models, namely the Interacting Shell Model (ISM), Microscopic Quasiparticle-Phonon Model (MQPM) and microscopic Interacting Boson-Fermion Model (IBFM-2) were compared against the measured beta spectra of the granular detectors of the COBRA demonstrator. The resulting values for the axial coupling are 0.893(0.054) for the ISM, 0.968(0.056) for the MQPM and 0.809(0.122) for the IBFM-2, indicating that consistent results for the three models of quite different nuclear many-body backgrounds could be achieved. The resulting computed beta spectra for these ranges of g-A values have been depicted in figure 1 where the spectral shapes for the g-A ranges of each model (shaded area) have been superimposed over the spectral shapes corresponding to the central values of g-A for the other two nuclear models (solid and dash-dotted curves). It is seen that an overall consistency between the predicted spectral shapes for the three models is achieved.

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[1] K. Blaum, S. Eliseev, F. A. Danevich, V. I. Tretyak, S. Kovalenko, Yu. N. Novikov and J. Suhonen, Reviews of Modern Physics 92, 045007 (2020)

[2] A. Kumar, P. C. Srivastava, J. Kostensalo and J. Suhonen, Physical Review C 101, 064304 (2020).

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

[4] A. de Roubin et al., Physical Review Letters 124, 222503 (2020)

[5] S. J. Haselschwardt, J. Kostensalo, X. Mougeot and J. Suhonen, Physical Review C 102, 065501 (2020) [Editors' Suggestion]

[6] S. Al Kharusi et al., Physical Review Letters 124, 232502 (2020)

[7] L. Bodenstein-Dresler et al., Physics Letters B 800, 135092 (2020)

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 local nuclear theory group and experimental nuclear physics groups at the accelerator laboratory.

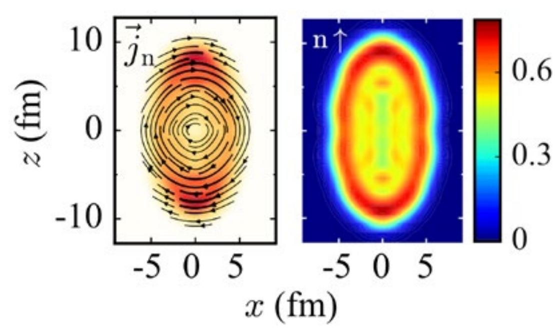
www.jyu.fi/science/en/physics/research/nuclear-and-accelerator-based-physics/fidipro-project

PROPERTIES OF SPHERICAL AND DEFORMED NUCLEI WITH REGULARIZED PSEUDOPOTENTIAL BASED EDFS

We have developed new nuclear energy density functionals (EDFs) based on a finite range pseudopotential [1]. The parameter adjustment was done for EDFs containing terms from the second-order in derivatives up to the sixth order. The results show that an order-by-order improvement of agreement with experimental data is possible and that the sixth order EDF describes data similarly or better than the standard Gogny or Skyrme EDFs. This comparison was done for a set of spherical and deformed nuclei, covering a wide range of mass numbers across the nuclear chart. Although definitive conclusions about the predictive power of the EDFs obtained in this study can only be drawn after comparison to a more diverse set of observables, developed EFDs look promising and pave a way towards EDFs designed to multi-reference beyond mean-field calculations.

NUCLEON LOCALIZATION FUNCTION IN ROTATING NUCLEI

The spatial electron localization function was originally introduced to characterize shell structure in atoms and chemical bonds in molecules. In nuclear structure physics, the nuclear localization function (NLF) can be used to identification of clusters in light nuclei and nuclear reactions, and the formation of fragments in fission. In this work, we studied NLF in a rotating superdeformed nucleus [2]. Our results indicate that NLF is an excellent indicator of the nuclear response to collective rotation and it can, e.g., reveal the pattern of rotational alignment in single-particle states.



↑ Figure 1. Calculated results for rotating superdeformed ^{152}Dy nucleus. The left panel shows the neutron current density and the right panel shows the spin-dependent neutron localization function for the x-component of the spin. A high localization value indicates that the probability to find two nucleons with the same spin and isospin at the location is low.

Selected publications

[1] K. Bennaceur, J. Dobaczewski, T. Haverinen, and M. Kortelainen, J. Phys. G: Nucl. Part. Phys. 47, 105101 (2020).

[2] T. Li, M. Z. Chen, C. L. Zhang, W. Nazarewicz, and M. Kortelainen, Phys. Rev. C 102, 044305 (2020).

RADIATION EFFECTS

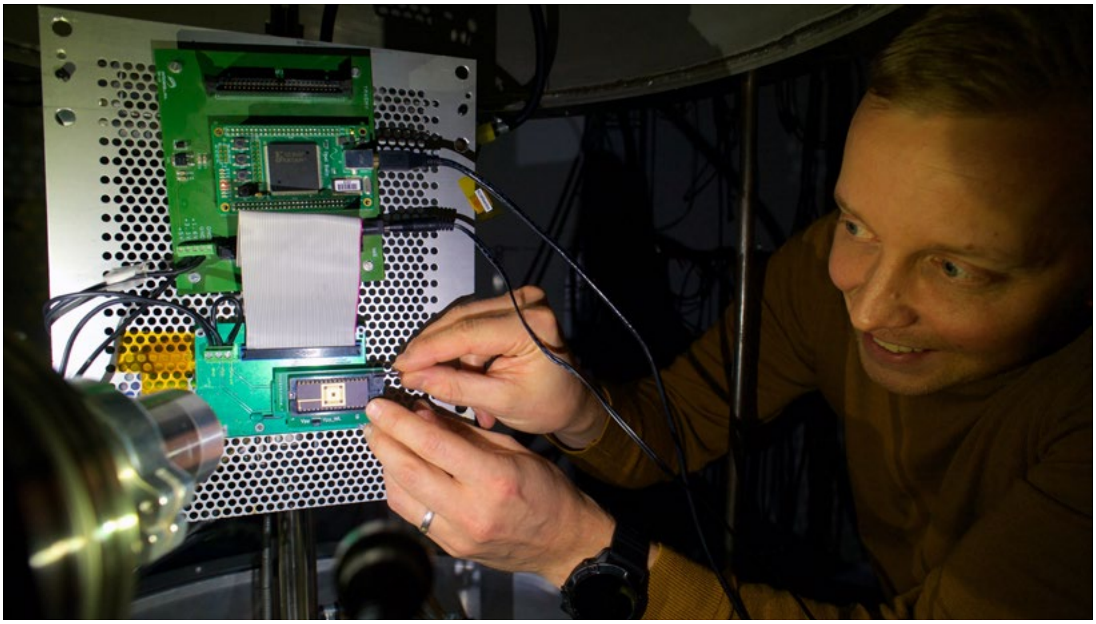
Staff scientist Heikki Kettunen
University researcher Arto Javanainen

We are specialized in applied research around nuclear and accelerator-based technology and operate the Radiation Effects Facility, RADEF, for the studies of radiation effects in electronics and related materials. RADEF officially became an ESA supported European Component Irradiation Facility (ECIF) in 2005. Since then, we have carried out irradiation tests not only for ESA and the European space industry, but also for other world leading space organizations (e.g., NASA, JAXA, CNES), companies and universities. The contract with ESA was again renewed in 2020 and will continue until the end of 2022.

www.jyu.fi/accelerator/radef

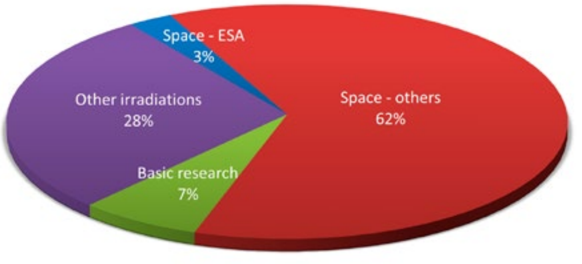
In addition to regularly used 9,3 and 16,3 MeV/n heavy ion cocktails, two new ion cocktails with energies of 10 and 22 MeV/n, including high LET value 10 MeV/n Au-beam, became available at RADEF in 2020. These attractive cocktails were developed together with our ECR group, which was part of their very successful HIISI ion source project.

Even year 2020 was exceptionally difficult to everyone, due to the COVID-19 pandemic and travel restrictions, RADEF was able to offer beam time even to foreign visitor mainly on the last part of the year. Some of the experiments were done remotely, but in major part, visitors came on-site. Big thanks to our customers who were willing to visit RADEF and follow all the quarantine, COVID-19 test and the other safety instructions.



↑ Figure 1. Jukka Jaatinen is setting up systems for remote test.

RADEF used 752 hours of K130-accelerator beam time in 24 campaigns with 19 different companies, institutes and universities. This corresponds to 20 % of the K130 beam time hours in 2020. The distribution of beam time between different users shown in Fig.1. The total revenue of RADEF (commercial, EU and ESA projects) in 2020 was about 900 k€.



↑ Figure 2. 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 will also perform simulation 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

Erasmus Mundus Joint Master Degree programme – RADMEP

University of Jyväskylä is part of the consortium, coordinated by University of St. Etienne (France), with KU Leuven (Belgium), and University of Montpellier (France) that will provide 2-year master degree studies for the next 4 consecutive years starting in fall 2021. The project RADMEP – "Radiation and its Effects on MicroElectronics and Photonics Technologies" offers multidisciplinary and innovative programme covering studies in the interactions between Radiation and MicroElectronics and Photonics, two Key Enabling Technologies for the future of Europe. RADMEP's objective is to educate students in those advanced technologies, providing methodologies and introducing practical applications for their implementation in a variety of natural or man-made radiation-rich environments.

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 will start 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

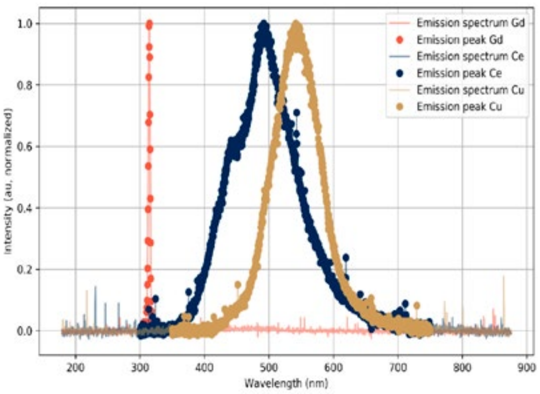
2017 under coordination of CERN. RADEF group is one of the seven beneficiaries and has also been heavily involved in the management of the project. The project has, for the first time, brought together the European industry, universities, laboratories and test facilities at this scale, and will eventually 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€.

STUDIES RELATED TO RADEF'S PHD STUDENTS

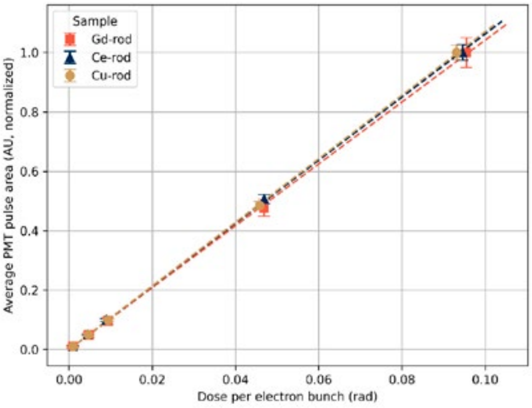
Dosimetry using optical fibres

Optical fibres can be used for real-time dose monitoring purposes, where one can accurately measure the deposited dose over time using a small measurement volume. The samples used here are silica rods, about 1 cm in length and 1 mm in width, doped with Gd^{3+}-, Ce^{3+}-, or Cu^{+}-ions, which exhibits radiation-induced luminescence (RIL) of photons when irradiated. The samples are spliced to silica glass optical fibres to transmit the RIL signal to a signal readout system.

At RADEF, the response of these samples to pulsed electron beams was studied. The measured emission spectra of doped samples are shown in Figure 3. The response of the samples when subject to electron bunches with different sizes is shown in Figure 4. All samples display a linear response between electron pulse sizes of 1 mrad to 0.1 rad in 3 µs long electron bunches.



↑ Figure 3. RIL spectra from silica glass samples doped with Gd, Ce and Cu.



↑ Figure 4. Output pulse area from PMT as a function of electron bunch size on the sample. Error bars are the standard deviation of the measured pulse sizes.

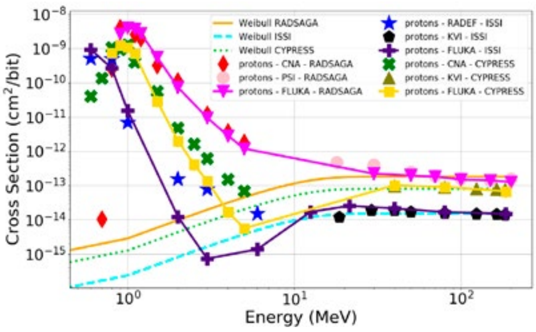
Relevance, guidelines and tools for radiation testing of components and systems to be used in complex environments

The scientific research was devoted to studying the impact of radiation effects from singly charged particles and their impact on standard hardness assurance practices. This included:

- The inelastic pion-silicon resonance and its effect on SEU and SEL cross-sections at high-energy as well as the pion absorption mechanism for low-energy SEL cross-section enhancements and consequences for accelerator hardness assurance.
- The proton direct ionization induced SEUs in custom-developed and commercial SRAMs, its modelling, the upset rate prediction method comparison and consequences for space hardness assurance.
- The use of high-energy electrons for displacement damage studies in place of protons or neutrons was further investigated on CMOS image sensors.

The technical research was devoted to writing guideline documents and to the cross-calibration of facilities. These include:

- The guideline for system-level radiation testing verification of space systems.
- The cross-calibration of novel thermal neutron facilities (TENIS at ILL and EMMA at RAL).



↑ Figure 5. Proton direct ionization SEU cross section enhancement in the RADSAGA 65 nm SRAM and two commercial SRAMs from ISSI and Cypress. FLUKA simulations show that the upset rate in typical Low-Earth Orbit for these devices would be dominated by proton direct ionization (> 90% of the total upset rate).

Selected publications:

A. Coronetti et al., "The pion single event effect resonance and its impact in an accelerator environment," IEEE Trans. Nucl. Sci., vol. 67, no. 8, pp., August 2020.

A. Coronetti et al., "Assessment of Proton Direct Ionization RHA for deep sub-micron SRAMs used in Space Applications," submitted for publication in IEEE Trans. Nucl. Sci.

A. Coronetti et al., "RHA through system level testing: Risk Acceptance, Facility Requirements, Test Methodology and Data Exploitation," submitted for publication in IEEE Trans. Nucl. Sci.

A. Coronetti et al., "The pion SEL cross-section enhancement: mechanisms and consequences for accelerator RHA," submitted for publication in IEEE Trans. Nucl. Sci.

Radiation effects on silicon carbide power devices

Silicon carbide (SiC) power devices are of great interest for space, avionic and accelerator applications. However, the current technologies are still very susceptible to radiation, which can degrade or destroy the devices. The focus of this project is to investigate the physical failure mechanisms induced by heavy-ions, protons and neutrons on SiC power MOSFETs. This work involves collaboration with Cern, ETH Zürich, Vanderbilt University, Helsinki Institute of Physics, Helsinki University and NASA.

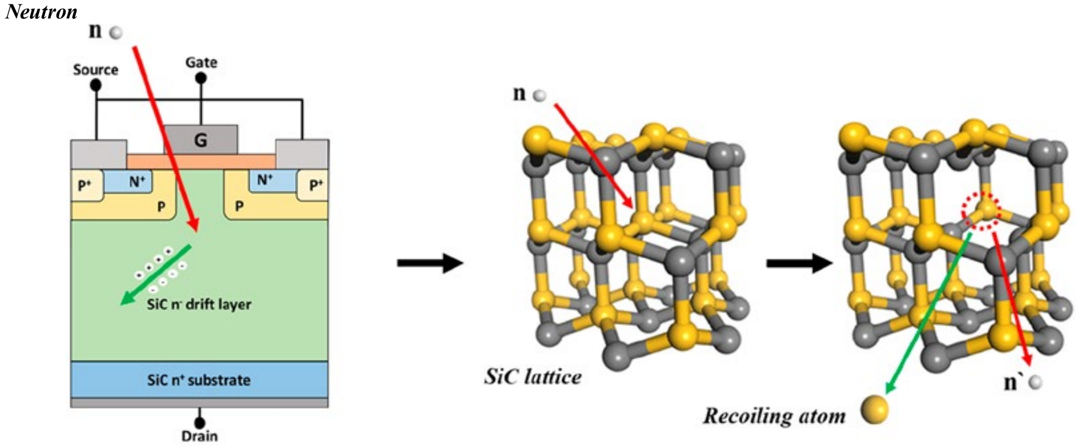
The effects of heavy ions on SiC power MOSFETs and diodes, were previously studied through radiation tests, Molecular Dynamics (MD) and Technology Computer Aided Design (TCAD) simulations. The radiation test campaigns continued in 2020 and included protons and neutrons. The radiation tolerance of several commercial technologies available on the market was studied, providing important results for avionics and accelerator applications.

Selected publications:

A. Javanainen *et al.*, "Heavy ion induced degradation in SiC schottky diodes: bias and energy deposition dependence," IEEE Trans. Nucl. Sci., vol. 64, no. 1, pp. 415-420, Jan. 2017.

C. Martinella *et al.*, "Heavy-Ion Microbeam Studies of Single-Event Leakage Current Mechanism in SiC VD-MOSFETs," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 7, pp. 1381–1389, Jul. 2020.

C. Martinella *et al.*, "Impact of Terrestrial Neutrons on the Reliability of SiC VD-MOSFET Technologies", accepted for publication in *IEEE TNS*, February 2021.



↑ Figure 6: Schematic of the neutron-induced damage in a SiC power MOSFET. By the elastic and inelastic scattering with the 4H-SiC lattice, neutrons produce recoiling atoms (i.e, a, C, Si, Mg, Al) which generate ionizing tracks inside the device.

ION SOURCES

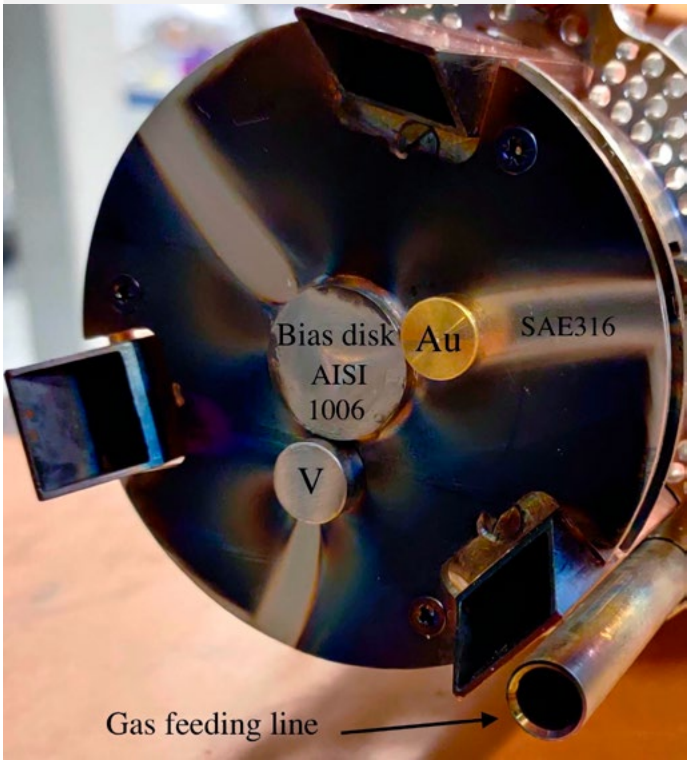
Senior Lecturer Hannu Koivisto

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 HEAVY ION SOURCE HIISI

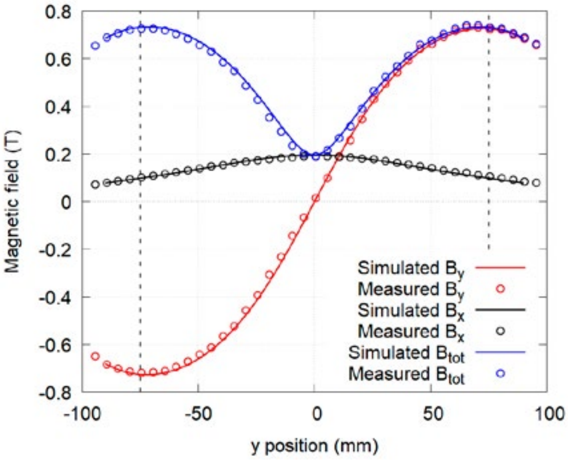
After a short commissioning period, HIISI has been routinely used for the nuclear physics program when high beam intensity, high charge states or high beam stability is required [1]. The source was vented and inspected in the beginning of 2020 revealing that regardless of the high microwave power (≈ 3 kW) no signs of plasma chamber erosion or overheating were found. This demonstrated that the unconventional cooling scheme of HIISI plasma chamber allows reliable, long-time operation without interruptions. Two short test periods were realized to develop highly charged V and Au ion beams for the space electronics testing program. The material injection into the HIISI plasma was made possible via plasma sputtering by mounting V and Au samples in the plasma flux area on the injection end of the ion source plasma. Figure 1shows the injection structure of HIISI and locations of V and Au samples. The center of the bias disk covering most of the injection structure facing the plasma is made of magnetic iron (AISI 1006) to maximize the injection magnetic field value (2.8 T). As a result of the arrangement, the requested ion flux of 10^5 particles/s/cm^2 for $^{51}V^{18+}$ and $^{197}Au^{54+}$ ion beam intensities were exceeded on the experimental target. Also, work to improve the ion beam extraction from HIISI has been initiated with the goal to improve the beam formation and the overall performance of the ion source.



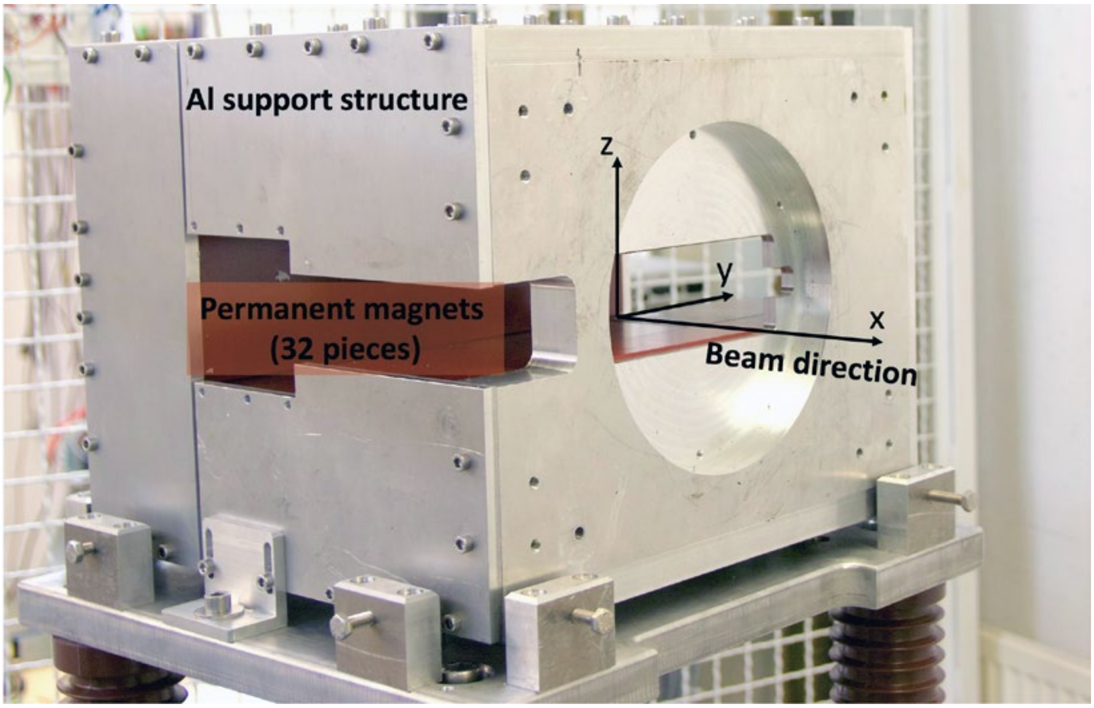
← Figure 1. Injection geometry of HIISI including samples for V and Au ion beam production.

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 structure on the performance of an ECR source"*. As a part of the project an innovative ECR ion source called CUBE, which magnetic field structure differs significantly from the conventional one, will be realized. The magnetic design, which bases on the use of permanent magnets, together with the extraction scheme have been presented in ref. [2]. The permanent magnets (32 pieces, mass ≈ 180 kg) were assembled into the aluminum support structure in fall 2020, and the measured magnetic fields agreed well with the design values as is shown in Fig. 2. Figure 3 shows the CUBE prototype on the HV insulated stand and the permanent magnets inside the aluminum frame. The first plasma is expected during the spring of 2021 and the first ion beam during the fall of 2021.



↑ Figure 2. Comparison of simulated and measured magnetic field of the CUBE-ECRIS. Plasma chamber walls are indicated with dashed vertical lines.



↑ Figure 3. Status of the CUBE prototype (December 2020).

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. The first experimental campaign of the project revealed new information about the correlation between the energy distribution of magnetically lost electrons (LEED) and rf-scattering [3]. The second measurement campaign offered an explanation to the observed different behavior of axial and radial bremsstrahlung emissions with varying magnetic field based on the directionality of plasma bremsstrahlung in ECRIS specific magnetic confinement scheme. Furthermore, it was observed that the onset of kinetic plasma instabilities has a clear impact on the shape of the LEED [4]. The third experimental campaign to study the parameters affecting the amplitude and the time structure of plasma instabilities was completed during the fall of 2020 and the data of this campaign is currently being analyzed.

A new method for determining Charge Breeder ECR Ion Source plasma parameters, based on the experimental data, was developed in collaboration with the LPSC and GANIL ion source groups. The method allows the calculation of the characteristic times of ionization, charge exchange and ion confinement, as well as estimates for the minimum average energy content of the plasma. The charge exchange, ionization, and confinement times affect the total time spent by a given particle in the plasma, and their optimization is of critical importance to the production of Rare Ion Beams (RIBs). Production of RIBs requires fast ionization to high charge states, while the confinement time must be long enough for the radioactive species to become ionized to the desired charge state, but short compared to its half-life for it to be extracted before it decays [5]. As a next step the experimental data obtained with the JYFL 14 GHz ECRIS will be used to evaluate the applicability of the method for the conventional ECR ion source.

Selected publications:

[1] H. Koivisto, A. Ikonen, T. Kalvas, S. Kosonen, R. Kronholm, M. Marttinen, O. Tarvainen and V. Toivanen, A new 18 GHz room temperature electron cyclotron resonance ion source for highly charged ion beams, Rev. Sci. Instrum. 91, (2020), p. 023303.

[2] T. Kalvas, O. Tarvainen, V. Toivanen and H. Koivisto, Design of a 10 GHz minimum-B quadrupole permanent magnet electron cyclotron resonance ion source, Journ. of instumentation, 2020 JINST 15 P06016.

[3] I. Izotov, A. Shalashov, V. Skalyga, E. Gospodchikov, O. Tarvainen, V. Mironov, H. Koivisto, R. Kronholm, V. Toivanen, B. S. B Bhaskar, The role of rf-scattering in high-energy electron losses from minimum-B ECR ion source. Plasma Physics and Controlled Fusion, (2021), Early online.

[4] B.S. Bhaskar, H. Koivisto, O. Tarvainen, T. Thuillier, V.Toivanen, T. Kalvas, I. Izotov, V. Skalyga, R. Kronholm, M.Marttinen, Correlation of bremsstrahlung and energy distribution of escaping electrons to study the dynamics of magnetically confined plasma, Submitted to Plasma Physics and Controlled Fusion (2020).

[5] J. Angot, M. Luntinen, T. Kalvas, H. Koivisto, R. Kronholm, L. Maunoury, O. Tarvainen, T. Thuillier, and V. Toivanen, Method for estimating charge breeder ECR ion source plasma parameters with short pulse 1+ injection of metal ions, Accepted for publication in Plasma Sources Sci. and Techn., (2021).

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) application of ion beam techniques for materials studies. The key infrastructure of the group is the 1.7 MV Pelletron accelerator and all the research equipment in its beamlines. In the Nanoscience Center (NSC) clean room the group is an active user of a helium ion microscope (HIM) and a versatile atomic layer deposition (ALD) tool. The group is an active link between the two research infrastructures, Accelerator Laboratory and Nanoscience Center.

www.jyu.fi/physics/accelerator/abasedmat

SIGNIFICANT FUNDING FOR TOF-ERDA DEVELOPMENT

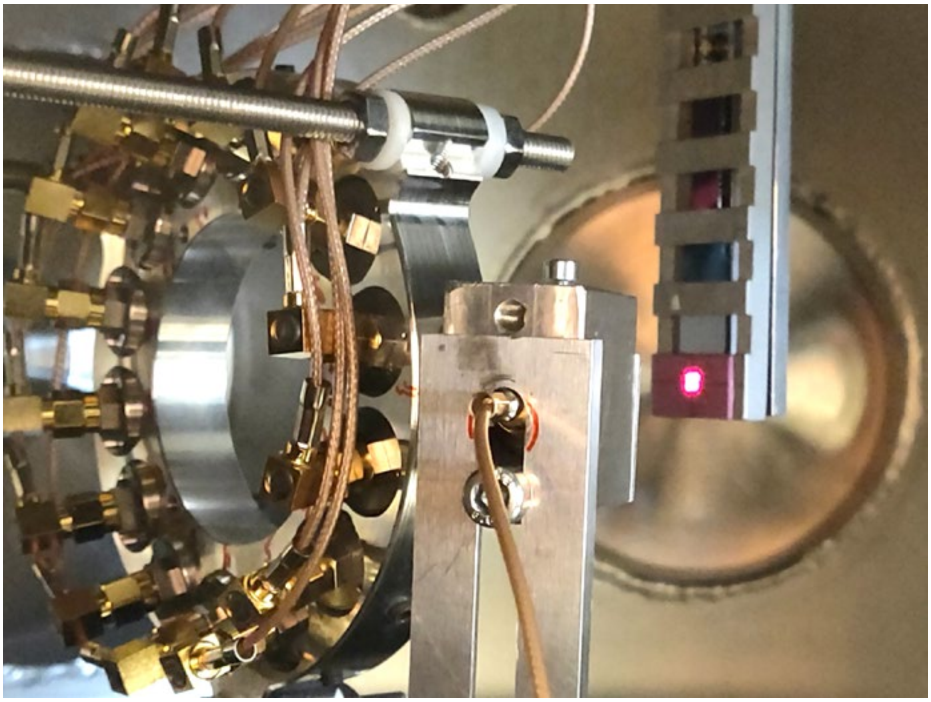
Staff scientist Mikko Laitinen started as an academy research fellow in a 5-year project concentrating on improving the ToF-ERDA quantification capabilities in measurements involving low energy heavy ions. In this project combinations of low energy heavy ions and heavy matrixes are measured in detail and the obtained results are used to improve the analysis procedure, possibly affecting also to the known theory of the scattering/recoiling processes. The project also aims at improving the detector telescope design towards faster and less sample damaging measurements.

The development of analysis software Potku continued during 2020 and had its 3rd joint development project with the JYU's IT faculty. In this project a web browser based ePotku project was run with more than 1000 hours of coding work. The difficulties to refactor the front-end (GUI) from the physics calculation based back-end hampered the browser/server-based project but the overall development of the Potku went clearly forward during the year. The first tutorial/webinar for the Potku was announced during the year 2020 and got positive feedback from the community. The software will be further developed in Laitinen's academy fellow project. Potku software is available from the department web pages (*https://www.jyu.fi/accelerator/pelletron/potku*).

The collaborative ion beam analysis and helium ion microscopy work continued in many fronts. The COVID-19 situation did prevent visitors through the RADIATE project but samples did travel and joint publications were written [1,2]. The other collaborations with research institutes and companies stayed active despite the pandemic.

RUTHERFORD BACKSCATTERING SETUP UPGRADE

The silicon detectors and aging NIM electronics of the RBS setup were replaced in 2020 by a new large solid angle detection setup. The upgraded system features 14 detectors mounted in a 160° scattering angle ring around the incoming beam. In addition, there is one movable detector, the angle of which can be varied from near zero to 145°. The signals from charge sensitive preamplifiers are connected to waveform digitizers that perform pulse height analysis on the on-board FPGA.



↑ Figure 1. RBS detectors and a 3.0 MeV $^4He^{2+}$ beam hitting a fluorescent screen.

The main advantage of the new detectors over the previous arrangement is the greatly improved solid angle, allowing measurements to be carried out rapidly with excellent statistics, while reducing the sample damage by the ion beam. The digitizing electronics further improves detection limits due to reduction in signal pile-up at high count rates.

ATOMIC LAYER DEPOSITION ACTIVITIES

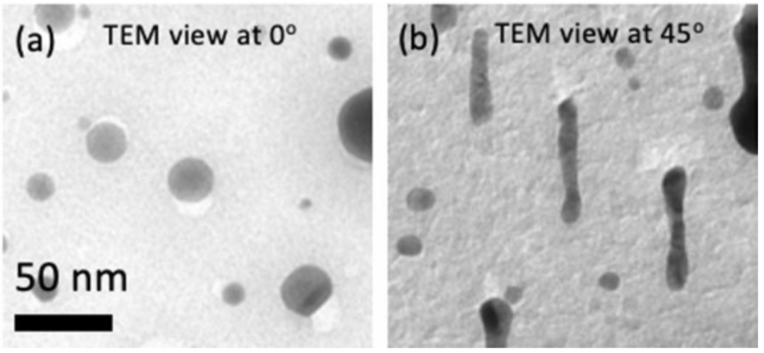
The ALD-Al_2O_3 films can contain as much as 20 at.-% of hydrogen if the deposition temperature is close to room temperature. In our study [3] we used heavy water ^2H_2O and oxygen-18 enriched water in order to study the origin of hydrogen in the films, and the migration and possible exchange reactions of hydrogen and oxygen in different temperatures. The concentrations of different isotopes were quantified by means of TOF-ERDA. The results showed that the origin of the hydrogen in the films changes from TMA to water as the temperature increases. It was also found that $^1H/^2H$ exchange reactions take place even at room temperature if the hydrogen concentration is high enough. On the other hand, oxygen atoms in the films do not migrate notably.

The ALD CoCampus activity with the JAMK University of Applied Sciences (Jyväskylä) intensified during the year 2020 in the form of one joint EU regional funds project (Lisäävä) and several commercial projects. Now Jyväskylä can offer access to both research scale (JYU) and production scale (JAMK) tools once the roll-to-roll WCS-500 reactor is in operation.

ION BEAM SHAPING OF EMBEDDED NANOPARTICLES

Ion beam shaping of embedded nanoparticles in solid-state matrix is a novel technique to fabricate new nanostructure morphologies. Previous experiments have revealed the transformation of metallic spherical nanoparticles to nanorods at high ion fluences >1013 ions/cm^2 under heavy ion irradiation. This phenomenon can be explained by modification of the matrix material by the ion track resulting in lower density (underdense) material and by flow of molten of the nanoparticle material into the matrix. The elongation has been observed this far in materials with metallic nanoparticles embedded in dielectric matrix, gold in SiO2 being the most studied system. So far, the research is focused only to initially spherical nanoparticles and a small number of matrix materials.

We have developed a new experimental approach allowing for imaging the same nanoparticles before and after irradiation with TEM (Transmission Electron Microscopy). In this way we can study in detail the shaping process as a function of the initial size and shape of the particle. Due to the requirement of the



← Figure 2: TEM images of 20 nm Si_3N_4/50 nm ALD SiO_2/NPs/50 nm ALD SiO_2 annealed sample irradiated with 50 MeV iodine beam at 5×10^{14} ions/cm^2 fluence containing spherical nanoparticles before (a) and after irradiation (b).

matrix underdensification, it can be expected that the elongation is sensitive to the matrix material properties, such as the composition, the density and the concentration of impurities. For this reason, we are currently testing different fabrication processes for the matrix deposition.

LASER ASSISTED SPUTTERING ION SOURCE

The recent hypothesis of ion pair production enhancement of beam currents from caesium sputter ion sources was tested by measuring the effect of various pulsed diode lasers on the O^- beam current produced from Al_2O_3 cathode [4]. Our experimental results provided evidence for the existence of a wavelength-dependent photo-assisted effect but cast doubt on its alleged resonant nature as the prompt enhancement of beam current can be observed with laser wavelengths exceeding a threshold photon energy. We conclude that the photo-assisted negative ion production could be of practical importance as it can more than double the extracted beam current from the ion source with suitable operational settings. These studies will continue 2021 with the collaborators from STFC, UK and Doshisha University, Japan.

RADIATING SCHOOLS!? -PROJECT FUNDED BY TIETEEN TIEDOTUS RY

A project led by Mikko Laitinen received more than 70 k€ external funding to build cloud chambers and tour them in more than 50 Finnish schools. The project will be realized during 2021–2022 together with the LUMA network of Finnish universities and JYU OKL (Department of Teacher Education). The project will explain and visualize the nature of ionizing radiation, present everywhere, with the cloud chambers to the young school students and to the general public.

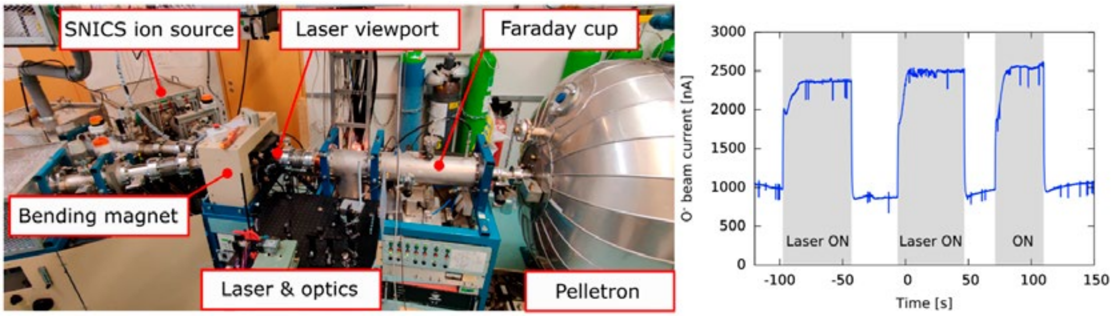
Selected publications:

[1] Z. Li, S.R. Kavanagh, M. Napari, R.G. Palgrave, M. Abdi-Jalebi, Z. Andaji-Garmaroudi, D.W. Davies, M. Laitinen, J. Julin, M.A. Isaacs, et al. *Bandgap lowering in mixed alloys of Cs2Ag(SbxBi1−x)Br6 double perovskite thin films*. Journal of Materials Chemistry A, 8 21780 (2020).

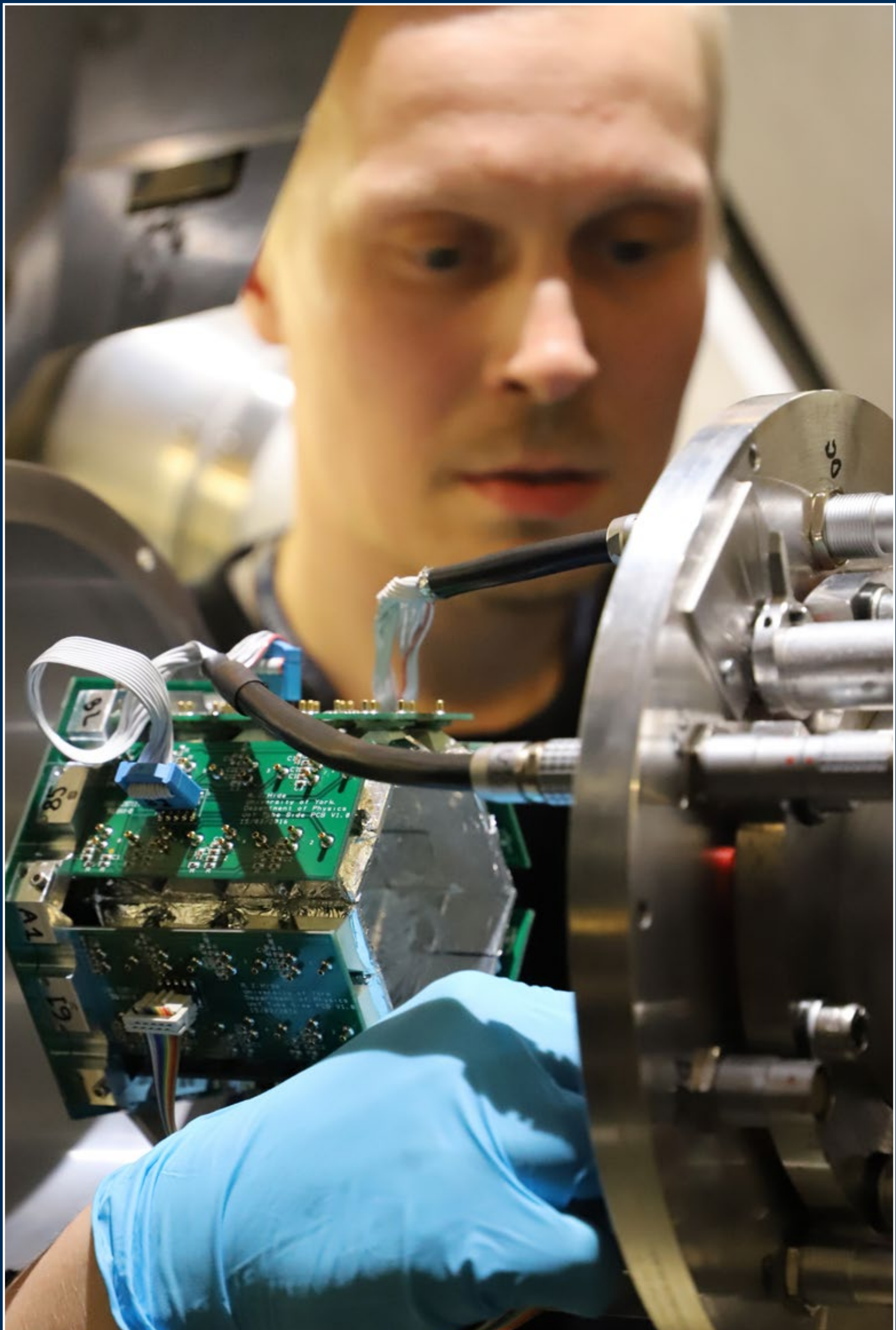
[2] M. Napari, T.N. Huq, T. Maity, D. Gomersall, K.M. Niang, A. Barthel, J.E. Thompson, Juliet, S. Kinnunen, K. Arstila, T. Sajavaara, R.L.Z. Hoye, et al. *Antiferromagnetism and p-type conductivity of nonstoichiometric nickel oxide thin films*. InfoMat, 2 769 (2020).

[3] S. Kinnunen, K. Arstila, T. Sajavaara, *Al2O3 ALD films grown using TMA + rare isotope 2H216O and 1H218O precursors* Applied Surface Science 546 148909 (2021).

[4] O. Tarvainen, R. Kronholm, M. Laitinen, M. Reponen, J. Julin, V. Toivanen, M. Napari, M. Marttinen, D. Faircloth, H. Koivisto, T. Sajavaara, *Experimental evidence on photo-assisted O− ion production from Al2O3 cathode in cesium sputter negative ion source.* Journal of Applied Physics, 128 (9), 094903 (2020).



↑ Figure 3. The laser setup used at JYFL-ACCLAB, illuminating the SNICS ion source cathode through the bending magnet viewport and the first results of the major, >100%, increase in the oxygen beam current by the 6 W/445 nm laser. Data from Ref. [4].



COSMOLOGY

Professor Kimmo Kainulainen
Senior Lecturer Sami Nurmi

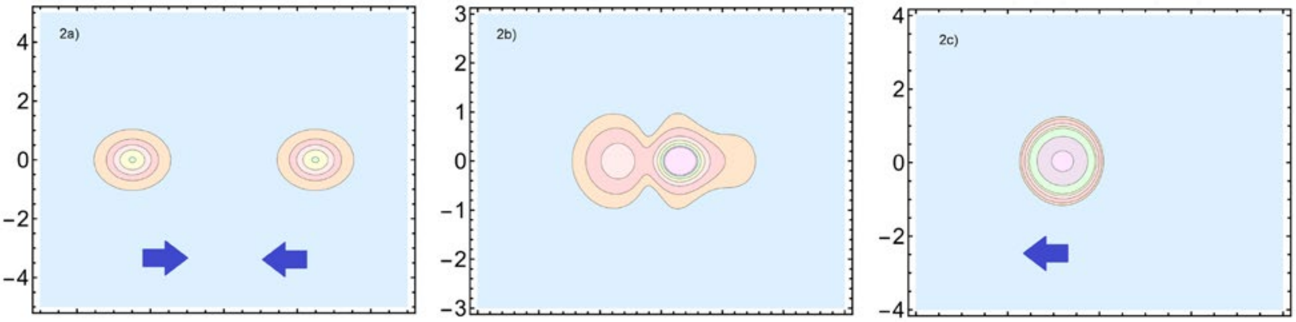
The work of the cosmology group during 2020 focused on dark matter (DM), electroweak baryogenesis (EWBG) and quantum transport theory, axion physics and several topics related to the physics of inflation. We also worked on the general constraints on the modified gravity and effective field theories of matter coupled to gravitation, where our bounds may be used to constrain general models of modified gravity and EFTs of matter coupled to gravitation.

DARK MATTER AND AXION PHYSICS

On methodology side, we developed fast and accurate tools for computing dark matter abundances using momentum dependent Boltzmann approach. Our methods allow precise evaluation of particle DM abundance when the relevant cross sections have sharp structures such as narrow poles, such as appear in popular higgs-portal models. Beside particle dark matter, an intriguing possiblity is that at least part of the DM is in form of axions, clustered to form macroscopic objects. These axion clumps could be observable when axions decay into photons, but the signal is strong enough only if these decays proceed via a parametric resonance. This requires that clumps are large enough, which may be achieved only through mergers of smaller clumps. We performed a careful analysis of such Axion star mergers using 3d simulations. While details of the merger-rate and accretion are heavily model dependent, it is possible that mergers lead to an appreciable photon flux on earth and we point out relevant observational search strategies.

We also studied an interesting connection between the particle dark matter and primordial black holes (PBHs). Indeed, DM particles can cluster around PBHs and then annihilate into gamma rays. We analysed this mechanism in detail in a representative DM model of thermal relic "winos" (an electroweak triplet fermion with a zero hypercharge). We showed that it is already possible to detect the characteristic gamma ray signal from such wino annihilations around a nearby solar mass PBH. This would be a novel discovery of a shining primordial black hole.

↓ Figure 1. A head on collision of two axion stars leading to a successful merger.

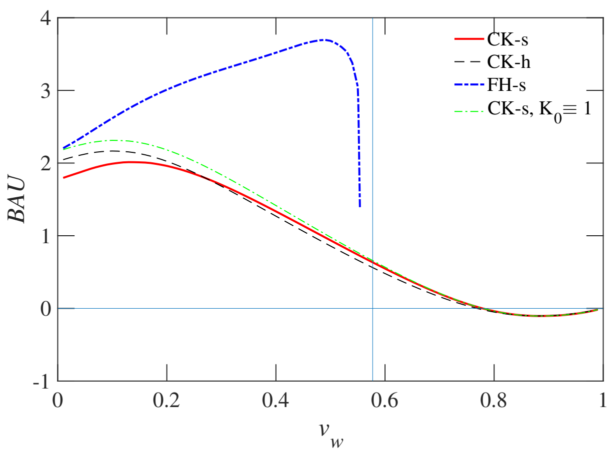


INFLATIONARY PHYSICS

Cosmological structures most likely originate from inflation. We investigated the microscopical mechanism of the process and its connection to theoretically motivated particle physics setups and we worked broadly on topics linked to primordial physics on the Higgs sector. Most recently, we made new progress to resolve the observational signatures related to gravitational couplings and quantum effects in the Higgs inflation model, and showed that the Higgs boson could efficiently source primordial perturbations even when it is not the inflaton field. Various out-of-equilibrium processes during inflation or reheating may lead to interesting observationally testable signals. Recently, we discovered a novel mechanism for dark matter production from gravitationally induced symmetry breaking during inflation. The aforementioned primordial black holes are also exciting objects that may be sourced by large quantum fluctuations formed during inflation. We develop new machinery to reliably predict the PBH abundance from inflation, and study their impacts on various observables.

ELECTROWEAK BARYOGENESIS AND QUANTUM TRANSPORT THEORY

Electroweak baryogenesis (EWBG) remains a prime candidate for the origin of the matter-antimatter asymmetry in the universe. Until recently it was widely believed that EWBG can only be efficient for wall velocities below the ”sound velocity barrier”. We showed that the baryon asymmetry evolves smoothly over the sound barrier and that EWBG can be efficient also for strong transitions associated with large gravitational wave signal. In a related work we studied a quantum system with a temporally changing particle mass, comparing accurate coherent quasiparticle methods (cQPA) with the semiclassical approach, analogous to one used in the EWBG context. We found that the semiclassical approximation works surprisingly well for very sharp temporal features. This is important for the EWBG with strong transitions, which are usually associated with narrow transition walls.



↑ Figure 2. Baryon asymmetry created in during the electroweak phase transition. Red line shows the correct smooth behaviour across the sound barrier.

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Massless positivity in graviton exchange, Mario Herrero-Valea, Raquel Santos-Garcia, Anna Tokareva. arXiv: 2011.11652.

Shining Primordial Black Holes, Mark P. Hertzberg. Sami Nurmi, Enrico D. Schiappacasse, Tsutomu T. Yanagida, arXiv:2011.05922.

Novel mechanism for primordial perturbations in minimal extensions of the Standard Model Alexandros Karam, Tommi Markkanen, Luca Marzola, Sami Nurmi, Martti Raidal, JHEP 11 (2020) 153. e-Print: 2006.14404

Merger of dark matter axion clumps and resonant photon emission, Mark P. Hertzberg, Yao Li, Enrico D. Schiappacasse, JCAP 07 (2020) 067, arXiv:2005.02405.

Electroweak baryogenesis at high bubble wall velocities, James M. Cline, Kimmo Kainulainen, Phys.Rev.D 101 (2020) 6, 063525, arXiv:2001.00568.

Quantum transport and the phase space structure of the Wightman functions Henri Jukkala, Kimmo Kainulainen, Olli Koskivaara, JHEP 01 (2020) 012, arXiv:1910.10979.

NEUTRINO AND ASTROPARTICLE PHYSICS

Senior Researcher Wladyslaw H. Trzaska

← Figure 1. Members of the NEMESIS Collaboration in front of the experimental setup in Callio Lab in the Pyhäsalmi mine.

JYFL involvement in experimental neutrino and astroparticle physics dates back to 2006 when we took the scientific responsibility for the Centre of Underground Physics in Pyhäsalmi, including the cosmic ray project EMMA. At that time European neutrino community was making plans for a giant detector of a new generation. The subsequent LAGUNA and LAGUNA LBNO Design Studies chose the Pyhäsalmi mine 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.

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

2020 has marked exciting developments in experimental neutrino physics. In February, the University of Tokyo, KEK, and J-PARC have jointly announced the approval of 3.5 billion yen for the first-year construction budget for the Hyper-Kamiokande project, due for completion in 2027. The Hyper-K detector will have 8.4 times larger fiducial mass that its successful predecessor the Super-K water Cherenkov underground tank. Next, four volumes of DUNE Technical Reports were published on arXiv and later appeared in JINST. A significant milestone for water-based scintillator detectors was the May 2020 EPJC publication of the THEIA white paper. There are no specific plans for THEIA's construction, but it remains a viable option for the "tank of opportunity" at the Sanford Underground Research Facility in South Dakota (SURF). While COVID-19 prevented us from face-to-face meetings, online participation has zoomed, literally. For instance, the traditional biannual Neutrino conference, initially aiming at 800

↑ Figure 2. Excavation of JUNO underground infrastructure

participants, ended up with 4,300 registrants. In June, the first blast has initiated excavation of the DUNE caverns at SURF. Over the next three years, 800,000 tons of rock will be drill-blasted and transported from the depth of 1.5 km to the surface and, on a 1.3 km long conveyer belt, to the open pit. The year ended with a bang, again literally when the final charge for the JUNO underground infrastructure excavation was detonated at 4 am on the 30th of December. The infrastructure includes the main detector hall, the water pool and all connecting tunnels. After six years of intensive work, underground civil construction is now coming to an end.

Here in Finland, our new setup continued taking data at a depth of 210 m.w.e. in the Callio Lab at the Pyhäsalmi mine. The setup, called NEMESIS (New Emma MEasurement with neutronS In cosmic Showers), incorporates infrastructure from the EMMA experiment with neutron and large-area plastic scintillator detectors of the MAZE system, contributed by our Polish collaborators from NCBJ. The experiment's primary aim is to combine muon tracking with position-sensitive neutron detection to measure precision yields, multiplicities, and lateral distributions of high-multiplicity neutron events induced by cosmic muons in various materials. The data are relevant for background evaluation of the deep-underground searches for Dark Matter, neutrino-less double beta decay, etc. The setup consists of four layers of position-sensitive muon counters, two large-area, amplitude-sensitive scintillators, and 14 He-3 proportional counters in polyethylene casting for neutron detection. The detectors surround a removable target. In 2020 we have completed a 300-day run with a 565 kg Pb target. With modest funding, it will be possible to implement a significant upgrade of the setup. It would improve the performance and increase the detection efficiency by one order of magnitude. The upgraded experiment would be well suited for searching for Dark Matter WIMP inelastic scattering events associated with an energetic charged lepton emission.

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DUNE Collaboration (2020). Long-baseline neutrino oscillation physics potential of the DUNE experiment. European Physical Journal C, 80 (10), 978. DOI: 10.1140/epjc/s10052-020-08456-z

IceCube-Gen2 Collaboration; JUNO Collaboration (2020). Combined sensitivity to the neutrino mass ordering with JUNO, the IceCube Upgrade, and PINGU. Physical Review D, 101 (3), 032006. DOI: 10.1103/PhysRevD.101.032006

W. Askins et al. (2020). THEIA: an advanced optical neutrino detector. European Physical Journal C, 80 (5), 416. DOI: 10.1140/epjc/s10052-020-7977-8

W.H. Trzaska et al. (2020). High-multiplicity muon events observed with EMMA array. Journal of Physics: Conference Series, 1468. IOP Publishing, 012085. DOI: 10.1088/1742-6596/1468/1/012085

QCD THEORY

Professors Kari J. Eskola and Tuomas Lappi

The QCD theory group studies different aspects of the strong interaction at high energy and density. In addition to the phenomenology of high energy nuclear collisions at the LHC and RHIC, we are involved with physics studies for planned colliders such as the EIC and FCC. We use weak coupling QCD renormalization group equations to understand the partonic structure of hadrons and nuclei. Our specialties also include using this information to understand the formation of a thermalized quark-gluon plasma and modeling its subsequent evolution with relativistic hydrodynamics. In 2020 Hannu Paukkunen started in a new Senior Lecturer position (AoF profiling action) and Ilkka Helenius obtained an Academy of Finland Research Fellowship. Meijian Li, Chris Flett and Florian Cougoulic started as new postdocs. Guillaume Beuf moved to a tenure track position at NCBJ Warsaw, and Gabriele Inghirami to a new postdoc position at GSI Darmstadt. Jani Penttala and Henry Hirvonen started as graduate students.

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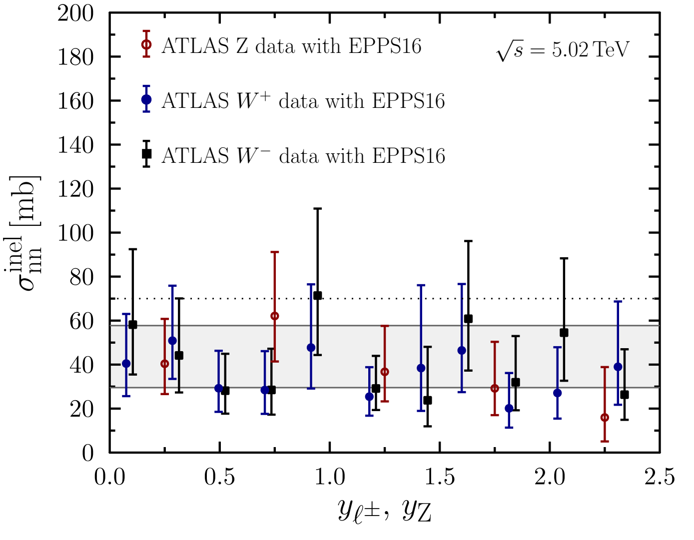
NUCLEAR PDFS AND SHADOWING IN INELASTIC NUCLEON-NUCLEON CROSS SECTION

We are leading the global analysis of nuclear parton distribution functions (nPDFs): our EPPS16 is the standard set in the field, and our earlier work introducing the EPS09 nPDFs became the first Finnish theoretical particle physics article that has reached 1000 citations. In 2020 we worked towards our next release, the "EPPS21" nPDFs, where LHC dijet and D-meson data will offer major new constraints for gluons. We also presented a new idea [1] of using the state-of-the-art EPPS16-supplemented perturbative QCD computation of electroweak boson production cross sections in nucleus-nucleus (AA) collisions as a benchmark with which one may determine the nuclear effects in the inelastic nucleon-nucleon cross section (σ_{nn}^{in}) from LHC data on Z and W yields. Using the ATLAS measurements, we found a rather significant suppression in σ_{nn}^{in} (Fig. 1), which clearly affects the Glauber-model-based extraction of the centrality-dependent nuclear modification factors for Z and W production in AA collisions.



↑ Figure 1. Extracted values of σ_{nn}^{in}: the fitted (gray band) and nominal (dashed line) values, compared with the ones corresponding to each rapidity in the ATLAS Z and W data. Figure from Ref. [1].

COLOR GLASS CONDENSATE AT NEXT-TO-LEADING ORDER MEETS HERA DATA

At very high collision energy, scattering of hadrons and nuclei starts to exhibit the phenomenon of gluon saturation, where nonlinear multigluon interactions become important. Theoretically, the physics of this gluon saturation regime can be understood in a coordinate space picture of eikonal scattering amplitudes, in contrast to the usual momentum space calculations used in the linear regime. In recent years, the total cross section for deep inelastic electron-proton scattering in this picture has been calculated to next-to-leading order in the QCD coupling by our group and collaborators. In 2020 we performed the first calculation [2] showing that these higher order cross sections result in a very good description of the total cross section data from the HERA collider at DESY, Germany. The agreement of the theory with the scattering data was very good using three slightly different formulations of the factorization between high energy renormalization group evolution (BK evolution) and the "impact factor" for the elementary scattering. This demonstrates the robustness and predictive power of the approach.

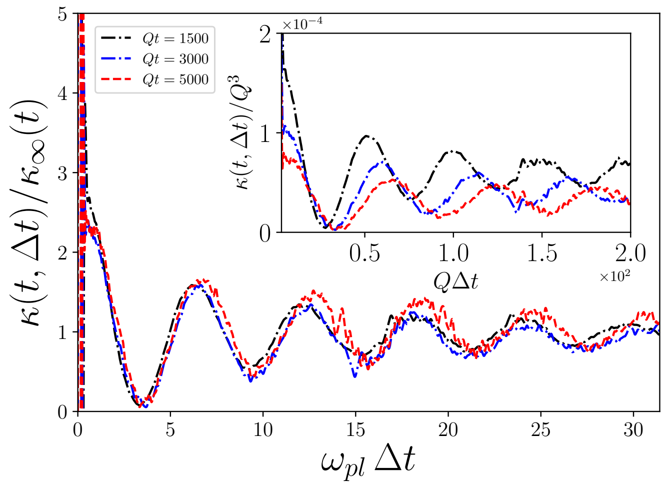
DIJET MEASUREMENTS AT THE ELECTRON-ION COLLIDER

The Electron-Ion Collider (EIC) is a proposed new high energy electron-proton and electron-nucleus collider, to be built at Brookhaven National Laboratory in the US. The year 2020 marked an important milestone for the EIC, which was officially adopted as a new construction project by the DOE. This started off a year-long "Yellow Report" effort to determine physics driven requirements for the detector design. Our group has very actively participated in this process.

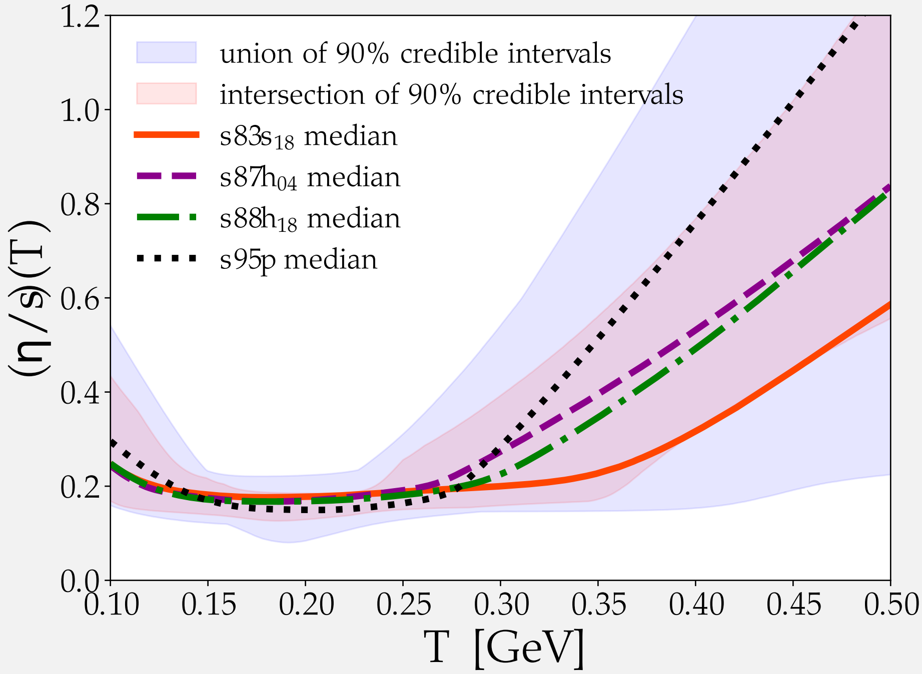
One of the key measurements at the EIC will be inclusive and diffractive dijet production. The correlations between the jet angles give access to the elusive Wigner distribution, which describes simultaneously the transverse momentum and coordinate distributions of the partons in the proton and the nucleus. In [3] we calculated cross sections for such processes. In particular, this calculation was performed in a more precise kinematics than in previous studies, and we showed that in some cases this full result deviates significantly from the "correlation limit" approximation widely used in the literature in the field.

HEAVY QUARK DIFFUSION IN AN OVEROCCUPIED GLUON PLASMA

Heavy quarks or jets can be used as tomographic probes of deconfined matter in a heavy ion collision. Traditionally, one has focused on the interaction of such probes with a plasma in thermal equilibrium. However, with the increasing precision of experimental measurements, it has become important to understand the interaction of these probes with the pre-equilibrium stage of the collision. In the Color Glass Condensate picture this early stage of a heavy ion collision is described in terms of a strong classical gluon field. In Ref. [4] we have determined for the first time the heavy quark diffusion coefficient in such an overoccupied gluon plasma, using classical Yang-Mills lattice simulations.



← Figure 2. Time dependence of the unequal-time color electric field correlator [4], from which one extracts the heavy quark diffusion coefficient as the large time separation limit. The inset shows the time separation measured in units of the hard scale Q, whereas in the main plot time is measured in units of the plasmon frequency. The scaling shows that the observed oscillations [4] scale with the plasma frequency.



↑ Figure 3. Temperature dependence of η/s obtained in Bayesian global analysis with different QCD equations of state. Figure from [5].

DETERMINING THE TEMPERATURE DEPENDENCE OF QCD MATTER Η/S

We studied the temperature dependence of the shear viscosity to entropy density ratio of QCD matter, (η/s)(T), via a Bayesian global analysis in Ref. [5]. We compared our EKRT model results with the hadron multiplicities, transverse momenta and elliptic flow coefficients measured in Au-Au collisions at RHIC and Pb-Pb at the LHC. In EKRT, we compute the initial quark-gluon plasma state from perturbative QCD and saturation. We then evolve the formed dense system in time and space using boost-invariant relativistic dissipative hydrodynamics with the QCD equation of state (EoS) as input. We introduced three new EoS parametrizations based on lattice QCD results and the hadron resonance gas picture. We showed that (η/s)(T) gets best constrained in the range T≈150-220 MeV, where $0.08<\eta/s<0.23$ within the 90% credibility intervals and where the EoS variations induce a ~10% effect on top of the overall ~30% uncertainty obtained (Fig. 3). Our new type of fit form for (η/s)(T) led to a slightly larger minimum value of η/s than in previous studies.

Selected publications

[1] K.J. Eskola, I. Helenius, M. Kuha, H. Paukkunen, Phys. Rev. Lett. 125 (2020) no. 21, 212301

[2] G. Beuf, H. Hänninen, T. Lappi, H. Mäntysaari, Phys. Rev. D 102 (2020) 074028

[3] H. Mäntysaari, N. Mueller, F. Salazar, B. Schenke, Phys. Rev. Lett. 124 (2020) 11, 112301

[4] K. Boguslavski, A. Kurkela, T. Lappi, J. Peuron, JHEP 09 (2020) 077

[5] J. Auvinen, K.J. Eskola, P. Huovinen, H. Niemi, R. Paatelainen, P. Petreczky, Phys. Rev. C 102 (2020) no. 4, 044911

ALICE EXPERIMENT AT THE CERN LHC

Senior Lecturer Sami Räsänen
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 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.

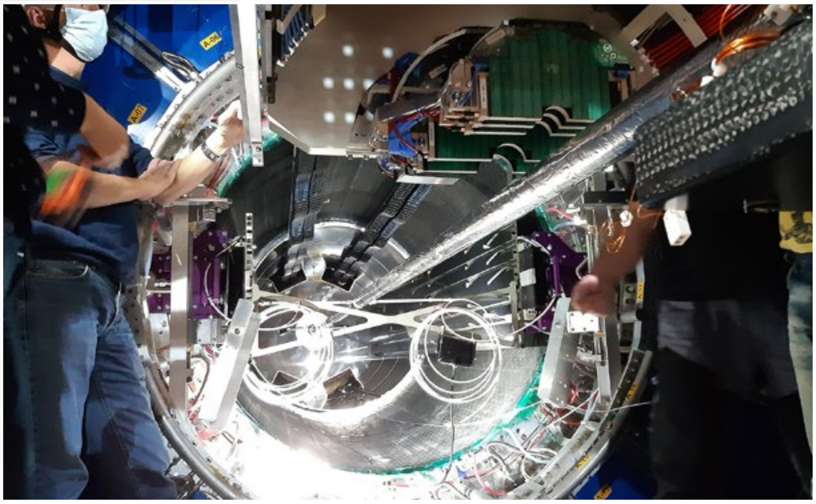
The ALICE physics program also includes proton-lead and proton-proton collisions. These lighter combinations provide a reference for Pb-Pb measurements and help to explore the limits of QGP creation with high-multiplicity events in small systems. In addition, ALICE measures basic interactions in the quantum-chromo dynamics (QCD). One of the 2020 highlights, published by Nature Physics [1], was a detailed study on interactions among baryons containing strange quarks.

The ALICE collaboration has over 1 900 members coming from 176 institutes in 39 countries.

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

In 2020 the second long shutdown (LS2) of the LHC had reached its mid-point. During the LS2 the ALICE experiment implements a major upgrade to cope with the increased luminosity of the Run 3. The improvements include three new detectors and continuous data readout with on-line reconstruction and data compression [2]. Our group makes a major contribution to the Fast Interaction Trigger (FIT). FIT consists of three sub-detectors arranged into five arrays of sensors. The FIT Collaboration involves 60 scientists from 19 institutions in nine countries. The University of Jyväskylä holds the leadership of the project since it was launched in 2014. In December 2020 the first FIT detector array, consisting of fast timing Cherenkov modules, was successfully integrated with the rest of the ALICE detectors. FIT installation is scheduled to be completed in June 2021.

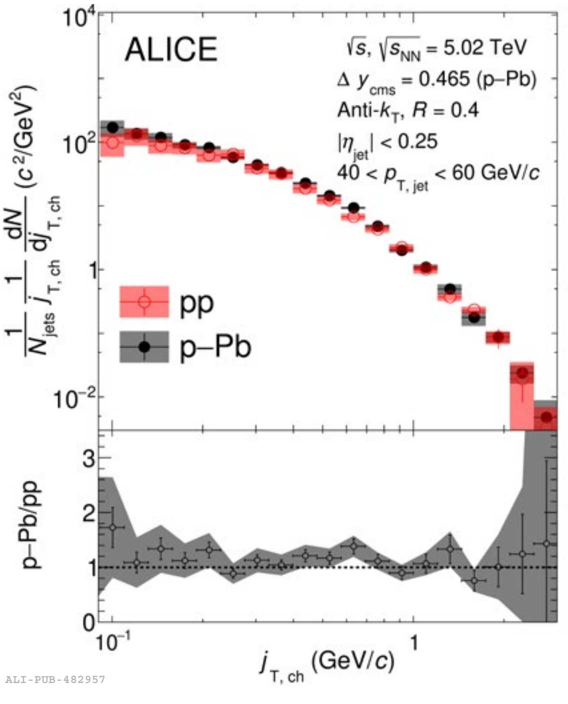
↓ Figure 1. Installation of the FT0-C component of the FIT detector array.



In June, Maciej Slupecki defended his PhD-thesis [3]. It was the first thesis fully devoted to FIT. Maciej's contribution included detector design, prototyping, construction and commissioning as well as software development. Maciej continues with us as a post-doctoral researcher stationed permanently at CERN. He serves as a FIT software coordinator and prepares for the FIT run coordination duties during the global commissioning and the first collisions.

↑ Figure 2. ALICE group at PhD-defence of Maciej Slupecki in June 2020.

In the physics data analysis, we continued to study collective flow and jets. A publication from higher harmonic flow modes [4] was driven by our group. These studies are essential in constraining the transport properties, like shear and bulk viscosities, of the QGP.



↑ Figure 3. Jet fragmentation transverse momentum distribution in p-Pb and pp collisions [5].

In the jet analysis, the results on the transverse structure in pp and p-Pb collisions of the jets were released to arXiv at the end of the year [5]. One puzzle in the field is that high-multiplicity events in small systems seem to exhibit collective behaviour. Still, one has not observed jet quenching that is clearly visible in Pb-Pb collisions. This study strengthened the earlier observations. We pursued studies on the puzzle by comparing collective like effects with and without bias to hard "jetty" events. The first results from the new analysis are published in 2021. Generally, ALICE approved an extended pp program in LHC Runs 3 and 4, where one of the aims is to collect a large data sample with the high-multiplicity trigger. In future, this data set will allow even more differential studies in small systems.

The 2020 ALICE approved additions for the LHC Run 4 include the new tracker and a forward calorimeter (FoCal). The relevant Technical Design Reports are now being drafted. We have initiated studies on physics performance of FoCal in neutral pion correlations and explore how to reduce the impact of secondary particles produced by material of FIT to the performance of FoCal.

[1] ALICE Collaboration, Nature 588 (2020) 7837, 232

[2] W.H. Trzaska, Nucl. Instr. and Methods A 958 (2020) 162116

[3] Maciej Slupecki, JYU dissertations, URN:ISBN:978-951-39-8186-0

[4] ALICE Collaboration, JHEP05 (2020) 085

[5] ALICE Collaboration, arXiv: 2011.05904 [nucl-ex]

INDUSTRIAL COLLABORATION

Professors Markus Ahlskog, Markku Kataja, Ilari Maasilta and Timo Sajavaara
Academy Research Fellow Mikko Laitinen
Staff Scientist Heikki Kettunen
Senior Researcher Arto Javanainen

The Radiation Effects group of the Accelerator Laboratory continued the utilization of RADEF facility under ESA's Technical Research Programme (TRP). The contract was again renewed in 2020 and will continue until end of 2022. In the contract, we are obliged to offer K-130 cyclotron beam time for ESA and European space industry. In addition, we provide irradiation tests with our LINAC electron accelerator. The use of RADEF's commercial beam time in 2020 was 752 hours corresponding to 20 % of the total running hours of the K-130 cyclotron. In total, 24 test campaigns for 19 companies were performed at RADEF. The commercial revenue in 2020 was about 900 k€.

RADEF is involved in several EU and ESA projects. 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). 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) will start 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 2020. In these ESA projects, RADEF acts as subcontractor.

The Thermal nanophysics group has well established collaboration with a few companies in Finland and abroad. The superconducting radiation detector work has involved collaboration with global, industry leading small and medium scale high tech companies, including one from the USA. In addition, national laboratories such as VTT Micronova, NIST Boulder, NASA Goddard Space Flight Center and Space Research Organization Netherlands (SRON) have been involved. In 2020, collaboration with globally leading nanofabrication tool companies continued, in particular with Raith GmbH.

During the year 2020, major research activity of the Complex materials group was devoted in developing experimental methods to support safety analysis of repositories of spent nuclear fuel. X-ray imaging and tomographic techniques were further developed and used in several industry-related projects to study the hydromechanical behavior of bentonite clay, planned to be used as a buffer material protecting the used fuel canisters in the deep underground deposition sites. The techniques used allow detailed 4D measurement of water transport and the resulting swelling deformation of the clay material. The results will be used in developing and validating numerical models used in long-time safety analysis. This work was carried out in the framework of KYT2022 Research Programme funded by the Ministry of Economic Affairs and Employment of Finland, and in two European consortium projects Beacon and EURAD, funded by EU/Horizon 2020 Framework Programme. The primary industrial partner in this research is Posiva. In addition, the industrial collaboration included several Finnish companies and applied research institutes such as VTT Technical Research Centre of Finland and the Geological Survey of Finland, GTK. During the year 2020 collaboration with industry was further promoted as two new shared research positions were initiated: Arttu Miettinen started in a Senior Researcher position shared with VTT, and professor Markku Kataja started as Chief Scientific Officer (part time) at Spinnova Oy.

←Figure 1. RPE Sami Rinta-Antila in a consultation assignment at the customer's site.

2020 continued the new Radiation protection expert (RPE) service, initiated by the legislation change in the previous year. By definition, the service is an expert consultation without a direct link to research, except through the Accelerator Laboratory scientists involved in the activity. Licensed RPE experts from the Accelerator Laboratory successfully negotiated permanent contracts to dozens of companies during the year. Two new detectors were bought with the commercial income, one with 17 keV threshold for photon dose rate and second detector also for neutrons. These detectors are naturally also available for the department's research personnel. The main advantage from the commercial RPE service to the department is not the money but the increased knowhow of the personnel via these industrial contacts and consultation projects. This strongly benefits the department's own radiation protection activities.

In 2020 the contract for the delivery of entire TOF-ERDA end-station and data acquisition system worth more than 0.5 M€ was signed. The delivery of the instrument is due in 2021 but in 2020 almost all of the design work and orders for the major components were made as well as commercial software licenses were bought. In total, this project requires close to 800 man-hours. Despite the COVID-19, the commercial analysis services using ToF-ERDA were actively used by companies with samples arriving in weekly basis.

The atomic layer deposition (ALD) activities towards the industry continued under the umbrella of ALD CoCampus together with the JAMK University of Applied Sciences. The project Lisäävä funded by EU regional funds brought together several companies interested in 3D printing and ALD. In addition, a joint research project (JYU share about 3 person-months) was conducted together with the Nestle company.

PHYSICS AND TEACHER EDUCATION

Professor Pekka Koskinen
University Teacher Jussi Maunuksela
Senior Lecturer Antti Lehtinen

COVID-19 PANDEMIC TRANSFORMED TEACHING OVERNIGHT

The year 2020 in education was dominated by the CODIV-19 pandemic. National measures against the pandemic triggered a transformation in teaching practices that took place over a single weekend, March 14th to 15th. All contact teaching — lectures, recitation classes, instructional meetings — went online. Student lab closed and exams took place at home. Web platforms earlier known to few, like Zoom and Teams, became standard environments for everybody. Lectures took place online until summer, and *ad hoc* do-at-home lab works were developed. The transformation was utterly challenging and exhausting, for students and teachers alike. The summer ended with a calmer situation, allowing for limited contact teaching and for opening the student lab during the fall. Although distant teaching and online tools made everybody miss proper eye contact and genuine presence of other people, online tools admittedly did demonstrate their usefulness and capabilities. It is likely that teaching will not fully return to the old practices even after the pandemic is over.

↑ Figure 1. A snapshot from our MOOC course, which teaches upper secondary school students also relativistic length contraction, a fascinating phenomenon completely omitted from their curriculum.

MODERN MOOC FOR MODERN PHYSICS

In the the year 2020 the concept of "lifelong learning" was introduced by force into the Finnish universities. In Jyväskylä, our department was among the pioneers to develop these new courses for lifelong learning. We developed and launched a MOOC course *Kvanttimekaniikkaa ja suhteellisuusteoriaa yleissivistävästi (Quantum mechanics and theory of relativity for the layman* in Finnish). In addition to serving lifelong learners, the course introduces the marvels of modern physics for upper secondary school students. By leveraging on popular physics questions and style of presenting, it thereby works as our shop window to strengthen recruitment efforts.

PIONEERING RECRUITMENT TO STRENGTHEN DEVELOPMENT OF TEACHING

The Department of Physics took pioneering measures to develop its teaching. Antti Lehtinen, with a MSc in physics (physics teacher education) and with a PhD in science education, was recruited as a senior lecturer with a shared contract between the Department of Physics and the Department of Teacher Education, initially with a 50/50 share between the two departments. The aim of this recruitment is to strengthen the collaboration between the two departments, bring new resources to development of teaching at the Department of Physics, and promote research on the teaching at the department.

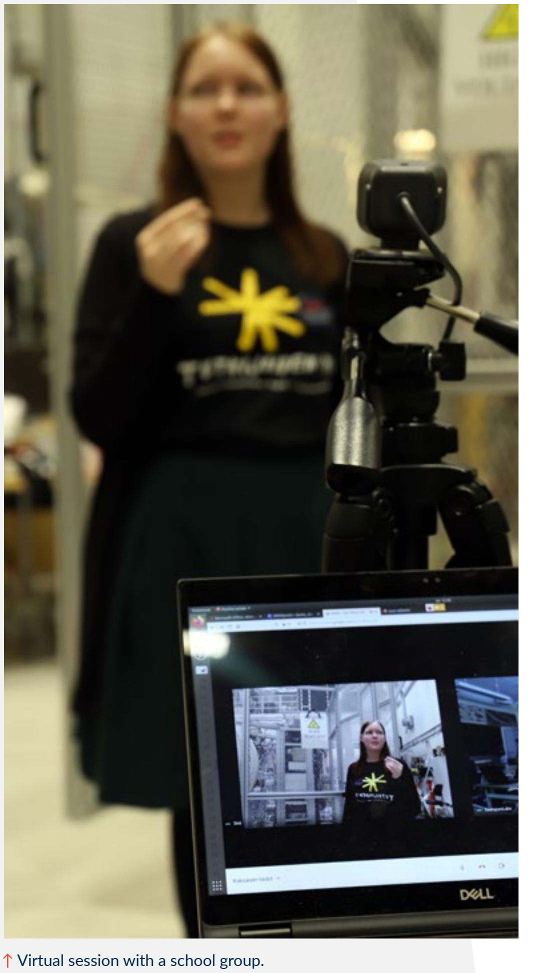
TUTKIJOIDEN YÖ RESEARCHER'S NIGHT

Staff Scientist Jan Sarén
Academy Research Fellow Mikko Laitinen
Senior Researcher Janne Pakarinen

The fifth Researchers' Night event at the Physics Department was organized on Friday 27th of November. Due to the pandemic situation the event was very different to previous years – now the event took place in virtual platforms employing YouTube live streams and videos, interactive online sessions and games. A new Departmental YouTube channel was created to host the event with a view to work as an archive for future videos filmed at the Department of Physics.

There were eight Finnish and English language online streams in total. The topics covered elementary research in nuclear physics, nuclear astrophysics, quark-gluon plasma, material sciences and satellite electronics facing the hostile environments of the outer space. Thanks to great speakers and well-prepared support teams, interactive online streaming was smooth and was considered a good experience in the unusual circumstances. Ville Mäkipelto, a well-known Finnish YouTuber, had prepared a video of his visit to the Department The video was released on the day of the Researchers' Night and has so far been collected more than 18 thousand views. Our researchers also answered the questions in the comment feed of the video. He was also interviewed by our Student Ambassador Nelma Peuhu. The interview has been watched 500 times. In addition to these, Ville's podcast series interview of professor emeritus Jukka Maalampi has gained already about seven thousand shows.

One of the best moments of the day was virtual session with the kindergarten and school kids who were very enthusiastic about our stories and demonstrations of magnetic fields, thermal radiation etc. We can be relaxed, a new generation of wonderful future physicists is growing.



↑ Virtual session with a school group.

Links to videos
https://tinyurl.com/h9wvw6hh ('Ville'),
https://tinyurl.com/shc877rf ('Nelma') and
https://tinyurl.com/dzj3m5cm ('Jukka').

↑ Light installation at Ylistö bridge

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