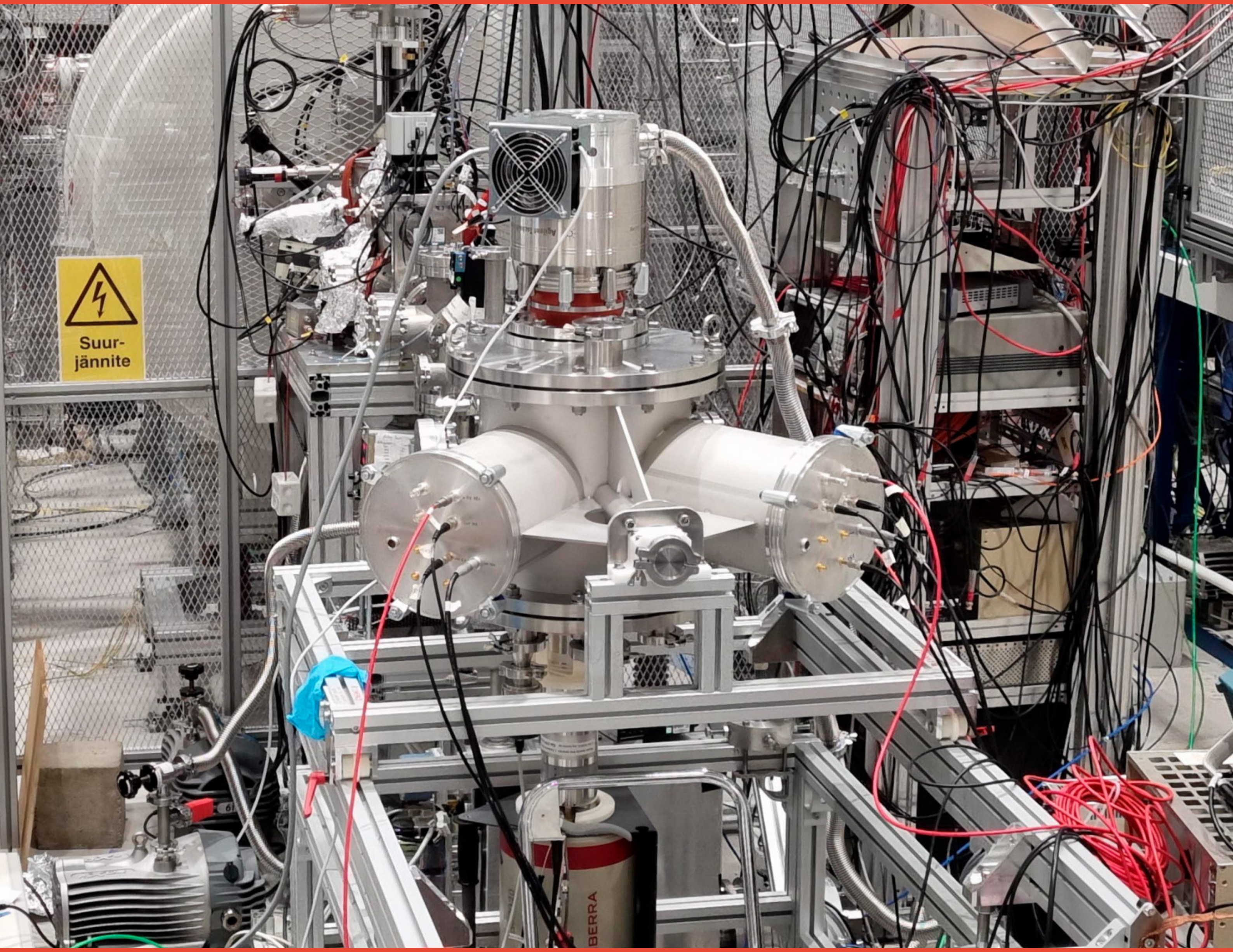

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

ANNUAL REPORT 2022
DEPARTMENT OF PHYSICS

For JYU. Since 1863.

DEPARTMENT OF PHYSICS

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

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

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

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

STATISTICAL DATA FROM 2022

174
PERSONNEL

- Professors incl. associate professors **20**
- Senior lecturers and researchers **22**
- Postdoctoral researchers **36**
- Doctoral students **58**
- Technical staff **29**
- ERC grantees **3**
- + Research assistants (MSc students) **9**

• Personnel counted in person-years

~280
UNDERGRADUATE STUDENTS
of which new students **52**
Doctoral students **~80**

23 BSC DEGREES

16 MSC DEGREES

7 PHD DEGREES

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

301
NUMBER OF FOREIGN VISITORS
Number of visits **381**

~250 Peer reviewed publications

~230 A1-A3 articles

~10 A4 Conference proceedings

~10 Other publications

15.5
FUNDING (million €)

- Basic financing **8.7**
- Sales (contract research) **1.5**
- Income according to separate laws (mainly EU funding) **1.7**
- Government grants **3.5**
- Other income **0.2**

CONTENTS

5 Preface

MATERIALS PHYSICS

6 The year 2022 at the NSC

EXPERIMENTAL NANOPHYSICS

7 Thermal Nanophysics and Superconducting Devices
9 Molecular Technology
10 Molecular Electronics and Plasmonics
12 Hybrid Quantum Technologies in Silicon
14 Synthetic Quantum Materials
15 Complex Materials

THEORETICAL NANOPHYSICS AND COMPUTATIONAL NANOSCIENCE

17 Computational nanoscience
19 Condensed matter theory
21 Quantum many-body theory
23 Low-dimensional nanomaterials modeling

NUCLEAR AND ACCELERATOR-BASED PHYSICS

24 Accelerator Laboratory
27 Nuclear spectroscopy
31 Exotic nuclei and beams
35 Instruments and Methods in Nuclear, Particle, and Astroparticle Physics
37 Nuclear structure and nuclear processes
39 Global properties of nuclei
40 Radiation effects
43 Ion sources
45 Accelerator based materials physics

PARTICLE PHYSICS AND COSMOLOGY

48 Center of Excellence in Quark Matter
49 QCD theory
52 ALICE experiment at the CERN LHC
54 Cosmology
56 Neutrino and astroparticle physics

58 Industrial collaboration
60 Teacher Education and Physics Education Research
61 Physics Education
62 Researchers' Night
63 Appendix: Research group members 2022

Editors:
Kari J. Eskola, Tuomas Lappi

Cover picture:
Alejandro Algora, IFIC, University of Valencia

Preface

This Annual Report provides an extensive summary of the activities at the Department of Physics during the year 2022.

The research within the Department of Physics is focused on experimental and theoretical materials physics, particle physics and nuclear physics. Most of the experimental nuclear physics research is carried out in the Accelerator Laboratory, one of the biggest research infrastructures in Finland, and particle physics has very strong connections to research and experiments performed in CERN. The materials physics research is concentrated in the interdisciplinary Nanoscience Center. In addition to research activities, the Department of Physics is one of the largest units in Finland educating BSc, MSc and PhD graduates in physics.

In the beginning of the year 2022, the main Covid-19 pandemic wave was already over but many of the restrictions were still in place and both remote working and remote teaching was a very common practice. During the spring the pandemic situation got better, after which the students and personnel returned to the campus. Even if the remote working and studying worked well for many, an even greater number of people suffered from those more isolated years. The smaller number of MSc and PhD degrees in 2022 can be associated to Covid-19 and many postponed degrees are expected in the coming years.

The start of the new Centre of Excellence in Quark Matter was the most significant development in our research in 2022. It is mainly funded by the Academy of Finland for eight years and led by professor Tuomas Lappi. The start of the new CoE has been very active and recruitments have been successful. A positive funding decision by the Academy of Finland for a FIRI project will bring a new 3 MV accelerator with ion and neutron beam possibilities in 2024–2025 to the Accelerator Laboratory. In 2022 the Department of Physics was not very successful in the Academy of Finland normal research project call, and this has put some pressure on the financial situation of the department.

The Department of Physics has a reputation for being a good working place, and working careers within the department are normally long. It is much more common to retire from permanent positions than to leave for other reasons. Anu Kankainen was promoted to full professor starting from January 2022. In May 2022 Kari Peräjärvi started in a five-year Professor of Practice position. Kari works as a Principal Advisor at the Finnish Radiation and Nuclear Safety Authority (STUK) and has a 20 % contract with JYU. His main task is to promote radiation safety research in JYU and the visibility of our research in relevant national and international networks. Riku Tuovinen was hired for a permanent senior lecturer position in theoretical nanophysics, and there were no retirements in 2022.

The Ylistö renovation did start in 2022 with the NSC clean room extension. The construction costs had increased substantially due to Covid-19 and Russia's attack in Ukraine (2/2022), and the original cost estimation was greatly exceeded. In 2023 the continuation of the renovation concerning the Department of Physics is unknown. On the other hand, the premises are still in good shape and no immediate need for the renovation is visible.

Timo Sajavaara
HEAD OF DEPARTMENT

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JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

THE YEAR 2022 AT THE NSC

Professor Jussi Toppari
Scientific Vice Director of Nanoscience Center

At the NSC the year 2022 started under the guidance of the new scientific director, Lotta-Riina Sundberg, who started a kind of a new era by being the first biologist as a director. This has included a subtle change in the atmosphere and already now one can spot more biologists within the corridors of the NSC, which have traditionally been dominated by physicists and chemists. This is a very welcome observation as it enhances communication between the disciplines and thus widens the collaboration possibilities.

Another reason for the increased number of perceived people is naturally the end of the Covid 19 restrictions, which have during the past few years driven us home and into our individual spaces. A clear evidence of folk returning to campus and to the labs is the coffee room, which has started to have the usual lively discussions again. In addition, we have now been able to organize events, such as the annual WeNSC, again on-site/live in Konnevesi research station. This has allowed us to connect more with each other and restrengthen the faded connections – and have fun! Also, our annual conference Nanoscience Days flourishes again as a real event in Agora.

During 2022, the NSC got a new physics group and PI as Arttu Miettinen with the tomography group joined the center. Even if not all the research done by the tomography group can be classified under nanoscience, the addition of the group was very natural, thanks to their traditions on modelling and imaging the physics within cells and other nanoscale objects. In addition, a new initiative was started to strengthen the collaboration between the Indian Institute of Technology (IIT) and NSC. This brought two new postdocs to the NSC with both of them contributing also to material physics research.

The year was also good for nanophysics funding. Our new assistant professor Shawulienu Kezilebieke got the renowned ERC starting grant for his STM research, and one full four-year project in theoretical physics was funded by the Jane & Aatos Erkko foundation. In addition, a new shared Marie-Curie fellow was funded between physics and chemistry.

However, the most visible changes in the NSC during the year were the many infrastructure renovations, which formed a starting point for the much wider renewal of the whole Ylistönrinne campus. Despite the deep troubles in the full renovation caused by the exploded material costs due to political situation in Europe, as well as inadequate supervision on the on the planning and construction site, the new clean room as well as the new STM laboratories were only slightly delayed at the end of the year. I hope the year 2023 will see them both in full operation.

All the best for the year 2023!

THERMAL NANOPHYSICS AND SUPERCONDUCTING DEVICES

Professor Ilari Maasilta

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

- Nanoscale thermal transport, especially focusing on phononic crystals and phonon tunneling
- Development of superconducting materials and devices, especially ultrasensitive superconducting radiation detectors and novel superconducting Josephson junction devices for quantum technology
- Utilizing novel nanofabrication and imaging techniques for interdisciplinary projects, such as nanoscale imaging with helium ion microscope (HIM) and 3D laser lithography

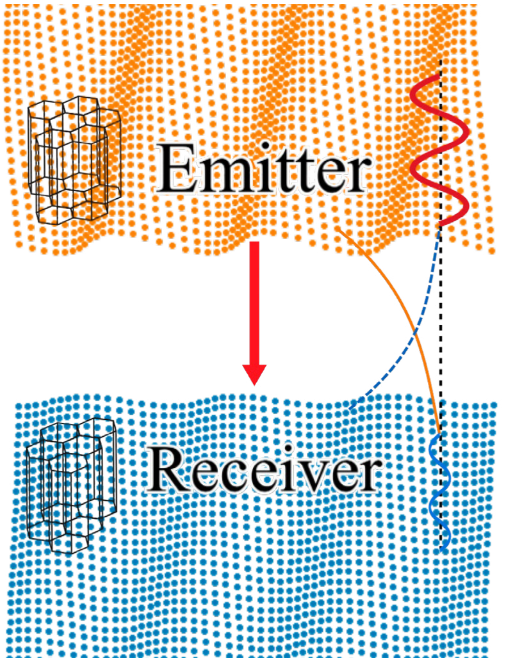
https://www.jyu.fi/en/research-groups/thermal-nanophysics-and-superconducting-devices

NANOSCALE THERMAL TRANSPORT

The year 2022 continued with a strong focus both on the theory and experiments of nanoscale thermal transport, although the published results in 2022 happen to reflect more the theoretical and simulation activities of the group. The first research highlight is the development of the first generally applicable theory of phonon tunneling across vacuum gaps, mediated by piezoelectricity [Geng2022a]. What we describe in detail in that study is how an acoustic wave (phonon) can jump from one piezoelectric crystal to another across a sizeable vacuum gap, even if the wave itself cannot exist in vacuum! This is possible because of the electric fields associated with acoustic waves in piezoelectric materials that decay into the vacuum. We have formulated the theory to be general enough to allow for the computation of the tunneling amplitude for any incoming acoustic phonon mode from any angle, for any anisotropic piezoelectric crystal symmetry and orientation, using anisotropic elasticity theory. Ongoing work addresses the impact of this phonon tunneling on the heat transfer, as a new channel of thermal “radiation”.

Another work highlights our collaboration with researchers from the CNRS Neel Institute in Grenoble, France, who observed in their sensitive experiments an unusually large low temperature heat capacity in thin suspended insulating plates made of SiN [Tavakoli2022]. Most plausible source for the excess heat capacity are the two-level fluctuators caused by structural disorder in amorphous materials such as thin film SiN. Interestingly, the internal stress of the plates, which was controlled by the growth method, had a large impact on the heat capacity. Our role in this study was to calculate the expected heat capacity based on elasticity theory of thin plates (Lamb-wave theory), which in the end could not explain the data.

We are still heavily focusing also on the physics of periodic phononic crystals. As an indication of the standing of our group in the field, we were invited to write a perspective article on a recent advance in a high impact journal [Maasilta2022].



↑ Figure 1. A schematic of phonon tunneling between two piezoelectric crystals. An elastic wave (phonon) from the emitter side impinges on the surface of the crystal, extending an evanescent (decaying) electric field in the vacuum. If the second crystal is within the wavelength of the acoustic wave, it is excited by the electric field and launches a tunneled wave, which continues to travel in the second receiver crystal.

DEVELOPMENT OF SUPERCONDUCTING DEVICES AND MATERIALS

The group's activities on developing novel superconducting devices continued in 2022. The main focus in 2022 was in the SUPERTED EU FET-open project to develop a novel superconductor-ferromagnet X-ray detector, which does not require external biasing, with experimental advances in developing the readout based on SQUID amplifiers and in fabrication and testing of the devices. We continued to develop the theory, as well, by formulating and solving the coupled thermal and electrical differential equations for the time-dependent response of the detector [Geng2022b], in other words, deriving the pulse response of the detector with realistic circuit models of the SQUID setup. In particular, we derived the conditions for the desirable case of non-oscillating decay, which can be used to optimize the detector and circuit parameters in the experiment.

Selected publications

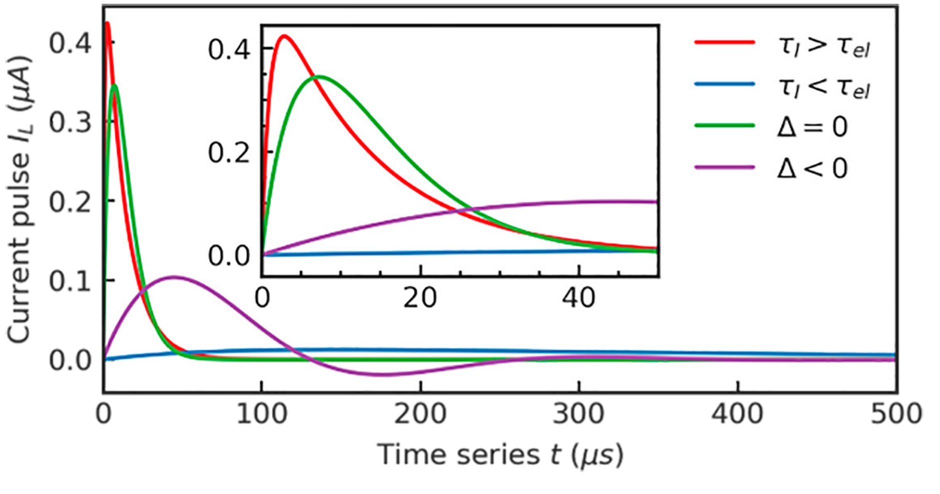
[Geng2022a] Z. Geng and I. J. Maasilta, *Acoustic wave tunneling across a vacuum gap between two piezoelectric crystals with arbitrary symmetry and orientation*, Phys. Rev. Research 4, 033073 (2022)

[Tavakoli2022] A. Tavakoli, K. J. Lulla, T. Puurtinen, I. Maasilta, E. Collin, L. Saminadayar and O. Bourgeois, *Specific heat of thin phonon cavities at low temperature: Very high values revealed by zeptojoule calorimetry*, Phys. Rev. B 105, 224313 (2022)

[Maasilta2022] I. J. Maasilta, *Phonons hushed*, Nature Nanotech. 17, 905 (2022)

[Geng2022b] Z. Geng and I. J. Maasilta, *Analytical Models for the Pulse Shape of a Superconductor-Ferromagnet Tunnel Junction Thermoelectric Microcalorimeter*, J. Low Temp. Phys. 209, 419 (2022)

↓ Figure 2. Simulation of SUPERTED X-ray detector pulses for different circuit and detector conditions. The green curve shows a good pulse with not-too-fast rise time and a non-oscillating fall time.



MOLECULAR TECHNOLOGY

Professor Markus Ahlskog

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

https://www.jyu.fi/en/research-groups/molecular-technology

TRANSPORT IN MWNTS

Arc-discharge synthesized multiwalled carbon nanotubes (MWNT) are of excellent quality compared to the more common CVD-synthesized MWNTs [1]. It is commonly thought that in high quality MWNTs the low bias conduction occurs solely in the outer layer, which is well founded if the outer layer is of metallic character. The transport gap in semiconducting MWNTs has a more complex behavior than the corresponding one in semiconducting single wall carbon nanotubes (Fig. 1(a)). In particular, we observe regularly negative differential resistance within this transport gap (Fig. 1(b)). In the typical case these properties can be explained as due to the involvement of the next inner layer in the conduction at modest bias voltages. We present a rough model for the transport characteristics that builds on a tunnelling resistance between the outer and second layer of the MWNT [2].

OTHER MEASUREMENTS ON MWNTS

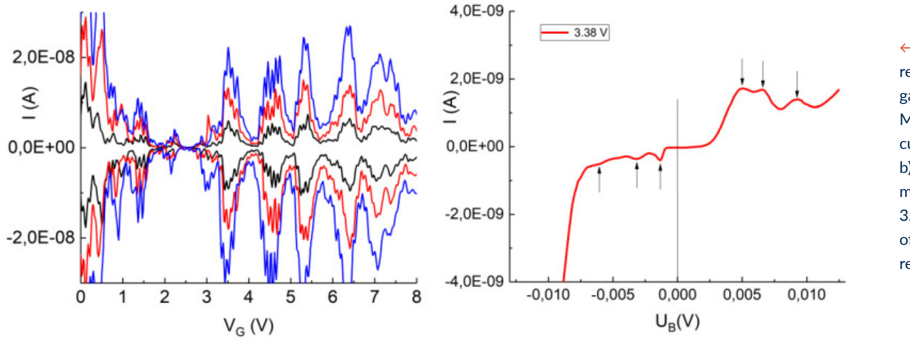
The complicated interlayer van der Waals (vdW) interactions can be investigated in individual MWNTs, prepared by our on-chip purification scheme. Our collaborators have, with polarized Raman imaging and spectroscopy, revealed the inhomogeneity of the Raman signal from individual high quality MWNTs. The splitting of the Raman-active G-band group is reported, describing it in terms of the variation of inter-layer mechanical vdW coupling as a function of diameter and interlayer distance in the probed AD-MWCNTs [3].

Selected publications

[1] M. Ahlskog, M.J. Hokkanen, D. Levshov, K. Svensson, A. Volodin, C. 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] M. Ahlskog, O. Herranen, J. Leppäniemi, D. Mtsuko, *Conduction Properties of Semiconductive Multiwalled Carbon Nanotubes*, European Physical Journal B, **95**, Nr. 130 (2022).

[3] M. Avramenko, M. Hokkanen, Y. Slabodyan, M. Ahlskog, D. Levshov, *Role of mechanical van der Waals coupling in G-band splitting of individual multi-wall carbon nanotubes*, Journal of Physical Chemistry C, **126**, 15759 (2022).



← Figure 1. a) The core region of the transport gap in a semiconducting MWNT, measured as current vs. gate voltage. b): Current vs. bias voltage measured at gate voltage 3.38 V. A strong behavior of negative differential resistance is seen.

MOLECULAR ELECTRONICS AND PLASMONICS

Professor Jussi Toppari

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

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

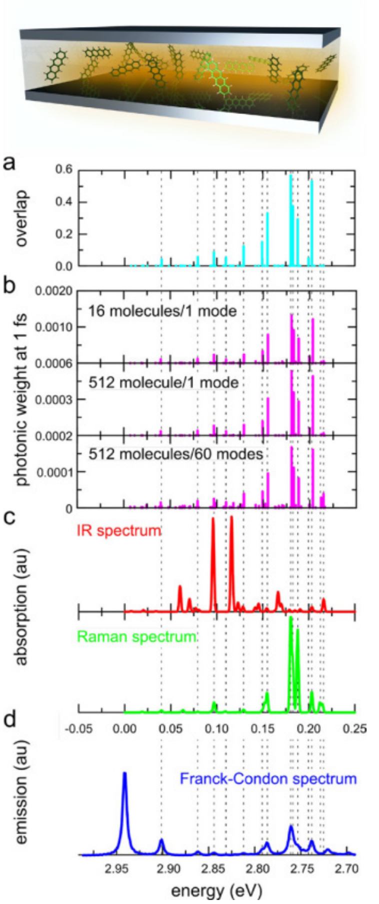
https://www.jyu.fi/en/research-groups/molecular-electronics-and-plasmonics

IDENTIFYING VIBRATIONS THAT CONTROL NON-ADIABATIC RELAXATION OF POLARITONS

The strong light-matter coupling regime, in which excitations of materials hybridize with excitations of confined light modes into polaritons, holds a great promise in various areas of science and technology. A key aspect for all applications of polaritonic chemistry is the relaxation into the lower polaritonic states. Polariton relaxation is speculated to involve two separate processes: vibrationally assisted scattering (VAS) and radiative pumping (RP). We have also earlier experimentally shown that the Stokes Shift of the molecule can dictate which process is dominating the system. However, the driving forces underlying these two mechanisms are not fully understood.

To provide more mechanistic insights, we performed multiscale molecular dynamics simulations of tetracene molecules strongly coupled to the confined light modes of an optical cavity. The results suggest that both mechanisms are driven by the same molecular vibrations that induce relaxation through nonadiabatic coupling between dark states and polaritonic states. Identifying these vibrational modes, as shown in figure 1, provides a rationale for enhanced relaxation into the lower polariton when the cavity detuning is resonant with specific vibrational transitions [1]. This work was done together with chemistry professor Gerrit Groenhof who is expert in multiscale molecular dynamics simulations.

To help designing experiments and interpret the results we have also developed a numerical method to model optical constants of organic molecular thin films from their absorption using a modified Lorentz oscillator model [2].



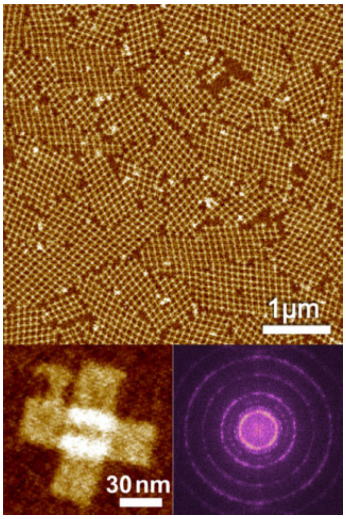
← Figure 1. On top is shown a schematic representation of a Fabry-Pérot cavity filled with tetracene (Tc) molecules (not to scale). (a) Overlap between the nonadiabatic coupling vector and the vibrational modes of Tc, plotted as a function of their energies. (b) Total photonic weight at 1 fs in simulations of 16 and 512 Tc molecules coupled to a single-mode cavity and of 512 Tc molecules coupled to a Fabry–Pérot cavity modeled with 60 modes. (c) Calculated infrared (IR) and Raman spectra of Tc. (d) Calculated Franck-Condon fluorescence spectrum, plotted with an inverted x-axis to match the normal mode energies. The dashed vertical lines are a guide for the eye.

TOWARDS METAMATERIALS BY DNA SELF-ASSEMBLY

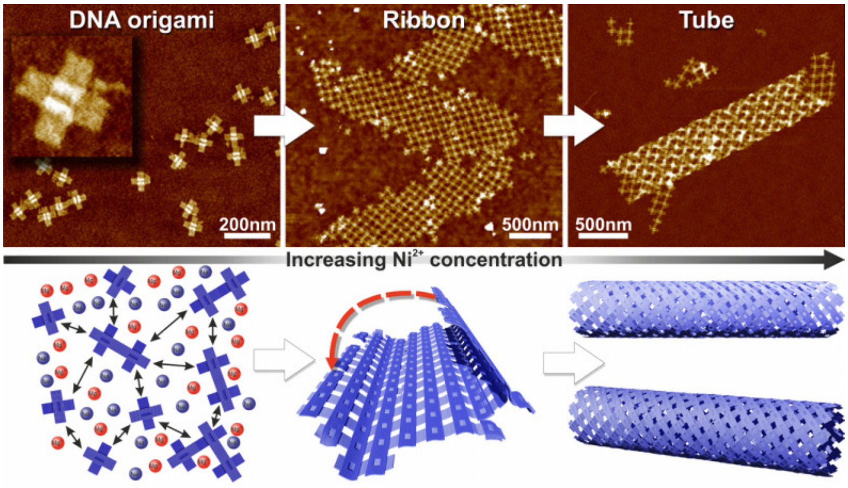
We develop DNA self-assembly-based methods to fabricate metallic, hierarchical nano-structures and -assemblies for nano-optics and plasmonics. During 2022, we have concentrated on fishnet type metamaterials, which have been shown to possess negative refractive index from long infra-red wavelengths down to the near infra-red. The operation range could be pushed even down to visible wavelengths by scaling down the features. However, this requires very precise lithography, such as e-beam lithography, which takes an enormous amount of time to cover the needed large surface areas.

Our goal is to combine our earlier developed DNA-assisted lithography (DALI) with the hierarchical self-assembly of DNA origami structures on the solid substrate to produce metallic extended 2D-lattices in a cost-efficient manner. DNA-origami lattices have been formed on a commonly utilized mica surface but that is, unfortunately, not compatible with any other microfabrication methods needed in DALI. We successfully adapted this self-assembled method to silicon surfaces and demonstrated the assembly of a 2D fishnet-type lattice on a silicon substrate using cross-shaped DNA origami as the building block, i.e., tile, as shown in figure 2 [3]. This is the first demonstration of self-assembled DNA-origami-lattices on silicon.

While constructing lattices out of cross-shaped DNA origami, we also developed a way to fabricate DNA tubes as shown in figure 3 [4]. By increasing the concentration of the Ni^{2+} ions used as a glue in Si-surface, we can drive the lattices to form ribbons and further tubes consisting of rolled DNA-origami-lattice.



↑ Figure 2. A large area AFM image of the 2D-fishnet-lattices self-assembled on a Si-substrate out of the cross-shaped DNA origami tiles, shown as a zoomed AFM image in the lower left inset. The lower right inset shows the Fast Fourier Transforms of the large AFM image revealing a clear periodicity of the lattices with period of 91 nm and 850 nm correlation length.



← Figure 3. Schematic view of the formation of the hierarchical nanostructures using the cross-shaped DNA-origami and electrostatic interaction. The lower row sketches the behavior of origamis with increasing Ni2+ concentration, while the upper row shows corresponding AFM images.

Selected publications

[1] R.H. Tichauer, D. Morozov, I. Sokolovskii, J.J. Toppari, G. Groenhof, *Identifying Vibrations that Control Non-adiabatic Relaxation of Polaritons in Strongly Coupled Molecule-Cavity Systems*, J. Phys. Chem. Lett. 13, 6259-6267 (2022).

[2] A. Dutta, V. Tiainen, H.A. Qureshi, L. Duarte, J.J. Toppari, *Modeling optical constants from the absorption of organic thin films using a modified Lorentz oscillator model*, Opt. Mater. Exp. 12, 2855-2869 (2022).

[3] K. Tapio, C. Kielar, J.M. Parikka, A. Keller, H. Järvinen, K. Fahmy, J.J. Toppari, *Large scale formation of DNA origami lattices on silicon* Chem. Mat., 35, 1961-1971 (2023).

[4] J. Parikka, H. Järvinen, K. Sokołowska, V. Ruokolainen, N. Markešević, A. Natarajan, A. Kuzyk, K. Tapio, J.J. Toppari, *Creation of ordered 3D tubes out of DNA origami lattices*, Nanoscale 15, 7772-7780 (2023).

HYBRID QUANTUM TECHNOLOGIES IN SILICON

Professor Juha Muhonen

We are an experimental group studying the interaction between spins, photons and phonons in silicon. Our motivation is both in enabling quantum devices and in studying the fundamental quantum phenomena.

Quantum technologies will be one of the defining technologies of our future. Quantum mechanical phenomena enables creating new kinds of sensors, communication methods and computers. A quantum computer will be a major shift in the computing capabilities of humankind, and we can dream of, e.g., full simulations of biological phenomena.

Specifically in our group we study how quantum computer components and quantum sensors could be realized using silicon. As silicon is the material basis of current information technologies, using that would enable leveraging the existing huge fabrication infrastructure and allow easy integration to classical electronics and quantum components.

https://www.jyu.fi/en/research-groups/hybrid-quantum-technologies-in-silicon

GROUP IN 2022

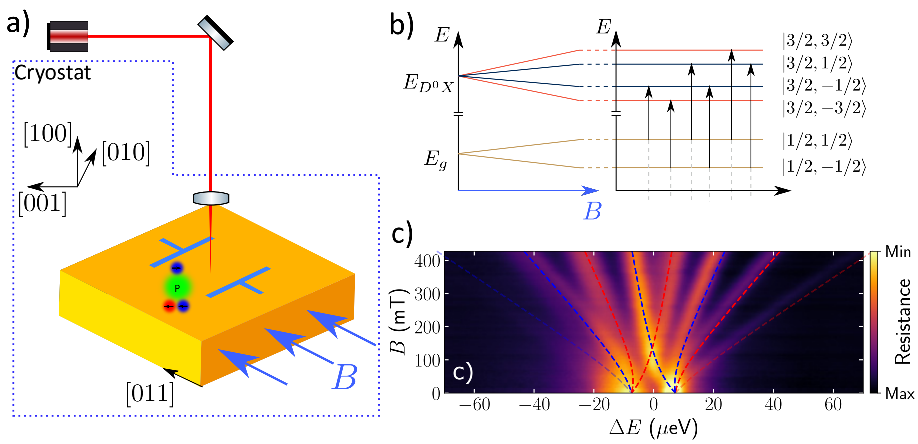
Our group had one more addition this year, as postdoctoral researcher Arvind Kumar joined the group in February! Arvind did his PhD at Case Western Reserve University in Ohio, USA. Hence our group had in the year 2022 two postdocs (Arvind and Henri Lyyra) and 4 doctoral students (Cliona Shakespeare, Teemu Loippo, Antti Kanniainen, and Charles Rambo).

OPTO-ELECTRICAL READOUT OF SPIN-STATES IN SILICON

This experiment [1] by Teemu and Antti studied how we can readout spin-states in silicon opto-electrically using microfabricated electrodes and how the strain caused by those electrodes affects the exciton properties.

Donor spin states in silicon are a promising candidate for quantum information processing, and one of our main research topics. Their application potential is still somewhat constrained by the lack of an optical interface, and achieving an optical spin readout is one of our main goals. One possible readout avenue is the donor bound exciton transition which can be spin-selectively excited using a resonant laser. The exciton, however, decays mostly via Auger recombination hence not enabling an efficient optical readout protocol. Nevertheless, hybrid opto-electrical readout, where the spin-selective transition is excited optically but the readout is done electrically, is possible, and this is what we studied here using phosphorous donors.

The opto-electrical readout has been demonstrated before but mainly in bulk substrates. Scaling the readout towards the single-spin level will require moving to microfabricated electrodes. As these electrodes will inevitably cause strain in the silicon lattice, it will be crucial to understand how strain affects the exciton transitions. Here we studied the phosphorus donor bound exciton transitions in silicon using hybrid electro-optical readout with microfabricated electrodes. We observe a significant zero-field splitting as well as mixing of the hole states due to strain. We can model these effects assuming the known asymmetry of the hole g-factors and the Pikus-Bir Hamiltonian describing the strain. In addition, we describe the temperature, laser power, and light polarization dependence of the transitions.



→ Figure 1. a) The measurement setup where we excite the exciton transition with laser and measure change in resistance of silicon with metallic electrodes on chip. b) The exciton transition schematic. c) The measured data showing resistance as a function of laser energy and applied magnetic field. The exciton transition lines are curved due to avoided crossings induced by the strain.

OPTOMECHANICAL FEEDBACK COOLING USING A SINGLE-LASER

This paper [2] by Arvind, previous group member Joonas and Henri, studied the feedback cooling of mechanical resonators. One of the main directions in our group is to try to use nanomechanical resonators as quantum transducers between different quantum systems. One major challenge in the use of mechanical resonators in quantum applications is their coupling to the thermal environment. It is an important challenge to cool these resonators close to their motional quantum ground state and minimize the phonon noise in the system. Somewhat counter-intuitively this cooling can be achieved with measurement-based feedback, similarly as in classical systems, even down to the quantum ground state. In this technique, the measured displacement of the oscillator is fed back into the sample as a force modulation that then allows for damping of the oscillator. This is usually done with a separate channel for measuring the motion and another one for inducing the force.

Here we study the case where only one laser beam is used for both probing and inducing the feedback force. The single-laser technique holds much promise due to its simplicity and efficiency of implementation. However, one could naively expect that the single-laser case would cause problems with both the ability to achieve significant feedback cooling and being able to interpret the homodyne signal as a readout of the mechanical displacement of the resonator. In this work, we analyze the single-laser feedback cooling through a classical analytical model - which is then validated through a numerical study - and further implement such a setup experimentally confirming the model.

A NOVEL WAY TO OPERATE A HOMODYNE INTERFEROMETER

In this joint publication [3] with a group from AMOLF (Netherlands), we demonstrated that operating a homodyne interferometer in a “quadrature-averaged” mode, we can simplify the extraction of optical cavity parameters when both resonant and non-resonant channels are present.

Balanced homodyne interferometry (BHI) offers a unique tool to characterize arbitrary quadratures of a light field with photon shot noise limited sensitivity and is in use in fields varying from detection of gravitational waves to quantum applications of cavity optomechanics. A common use case for BHI is to probe an optical cavity that is in one of the arms of the interferometer. Any frequency changes of that optical cavity are transferred into relative phase differences between the two interferometer arms.

Usually, the detection of the phase difference is performed by locking the local oscillator arm phase with regards to the (non-perturbed) signal phase by the means of a variable path length. Another method we use here is to average over all possible phases of the local oscillator by modulating the local oscillator slowly. Here we show that this quadrature-averaged BHI can be a useful method in characterizing optical cavities when the measured signal also includes light that has not interacted with the cavity (non-resonant reflection or transmission). This has applications especially in cavity optomechanics, and in other areas using nanophotonic cavities, where the non-resonant channels can be sensitive to the experimental conditions.

Selected publications

[1] T. Loippo, A. Kanniainen and J.T. Muhonen. Strain effects in phosphorus bound exciton transitions in silicon. *Phys. Rev. Mater.* 7, 016202 (2023).

[2] A.S. Kumar, J. Nätkinniemi, H. Lyyra and J.T Muhonen. Single-laser feedback cooling of optomechanical resonators. *Preprint*, arXiv: 2209.06029.

[3] G.R. La Gala, A.S. Kumar, R. Leijssen, E. Verhagen and J.T. Muhonen. Quadrature-averaged homodyne detection for cavity parameter estimation. *Preprint*, arXiv: 2209.05807. *Accepted to Physical Review Applied, in print*.

SYNTHETIC QUANTUM MATERIALS

Assistant professor Shawulienu Kezilebieke

We are a research group at the University of Jyväskylä studying synthetic quantum materials. We explore materials that exhibit mysterious and exotic phases of quantum matter, such as topological superconductivity, topological insulators, and collective behaviors of interacting electrons in materials with reduced dimensions, as well as spin properties of atoms and molecules on surfaces. To create designer quantum matter, we use MBE techniques to grow artificial materials layer by layer. After synthesis, we explore the electronic and magnetic properties of our artificial materials by state-of-the-art STM.

https://www.jyu.fi/en/research-groups/synthetic-quantum-materials-group

In 2022 we have finalized a tendering process for two STMs: 1K-STM under an external magnetic field up to 8T and 4K-STM combined with optical spectroscopy which allows us to perform STM-induced luminescence and tip-enhanced Raman spectroscopy down to angstrom spatial resolution. We have also ordered an MBE setup (received in May 2023, fully functional by October 2023) for growing artificial materials layer by layer. These facilities will be used for studying magnetic and optical properties of 2D van der Waals heterostructures.

Selected publications

[1] Somesh Chandra Ganguli, Markus Aapro, Shawulienu Kezilebieke, Mohammad Amini, Jose L Lado, Peter Liljeroth, 'Visualization of moiré magnons in monolayer ferromagnet'. Nano Lett. 2023, 23, 8, 3412–3417. *https://doi.org/10.1021/acs.nanolett.3c00417*

[2] Mohammad, A, Orlando, S, Viliam, V, Jose L, S, Foster, A, Liljeroth, P, Shawulienu, K 2023, ' Control of Molecular Orbital Ordering Using a van der Waals Monolayer Ferroelectric', Adv. Mater. 2023, 2206456. *https://doi.org/10.1002/adma.202206456*.

[3] Somesh C. Ganguli, Viliam Vaňo, Shawulienu Kezilebieke, Jose L. Lado, Peter Liljeroth 'Confinement-Engineered Superconductor to Correlated-Insulator Transition in a van der Waals Monolayer', Nano Lett. 22, 5, 1845–1850 (2022). *https://doi.org/10.1021/acs.nanolett.1c03491*

[4] Shawulienu Kezilebieke, Viliam Vaňo, Md N. Huda, Markus Aapro, Somesh C. Ganguli, Peter Liljeroth, and Jose L. Lado 'Moiré-Enabled Topological Superconductivity ', Nano Lett. 22, 1, 328–333 (2022). *https://doi.org/10.1021/acs.nanolett.1c03856*

COMPLEX MATERIALS

Senior researcher Arttu Miettinen

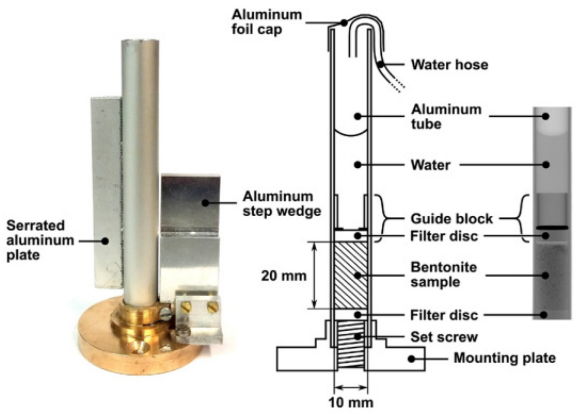
The research scope of the group includes X-ray tomography and 3D image analysis, heterogeneous materials, theoretical and numerical modelling, complex fluid mechanics and rheology, as well as their applications in various industrial problems. The group runs an extensive X-ray tomography laboratory that includes three X-ray scanners used in non-invasive three-dimensional imaging and analysis of the internal microstructure of a wide range of heterogeneous materials. The research topics of the group also include water kinetics in chemo-elastic clays, the micro- and nanostructure of engineered biomaterials, and image-based characterization of soil structure.

https://www.jyu.fi/en/research-groups/complex-materials

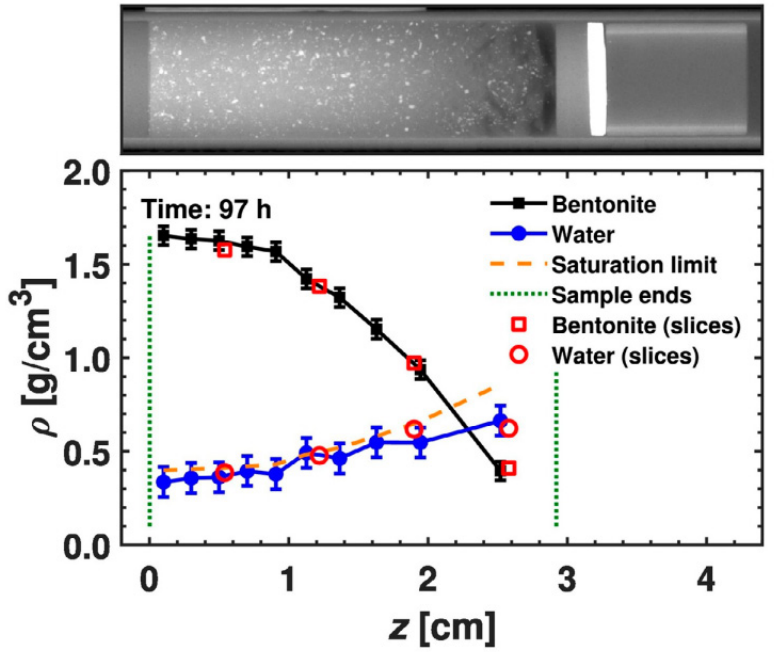
In 2022, we finalized the X-ray tomography laboratory update with an in-house developed JTomo micro-tomograph. The device features a 5 µm resolution, fast imaging speed, flexible control system, and two photon-counting detectors combined to a standard flat panel detector. The capabilities of this new infrastructure have already been taken advantage of in the ongoing HiiletIn project, where imaging techniques (tomography, HIM, SIMS) are applied in understanding organic carbon behavior in Finnish agricultural mineral soils. Other uses for the new infrastructure have been found from several projects related to the final deposition of radioactive waste in deep geological repositories, and product development work with industrial clients.

IN-SITU MONITORING OF WATER CONTENT IN RAPIDLY SWELLING CLAYS

We developed a non-invasive method based on X-ray imaging for determination of the local water content and deformation in rapidly swelling bentonite clay [1]. The method is based on taking sequential X-ray radiographs of the clay sample. A careful calibration procedure taking advantage of calibration plates of varying thicknesses accounts for non-idealities in the X-ray beam and detector. This allows for precise measurement of the local attenuation coefficient field in the sample material. A specific digital image correlation technique is used to calculate the deformation of the sample. Combined, the method can assess the temporal evolution of both water content and deformation of the clay material at the same time. Figure 1 shows the sample holder along with its schematics, whereas Figure 2 demonstrates a typical water content profile measured with the method. Validation data is also shown. In the depicted free swelling experiment, we were able to monitor both fast initial swelling happening in mere seconds, and slow late-stage swelling, where the relevant time scale is several hours. Such temporally multi-scale swelling phenomena are hard to observe with other methods.



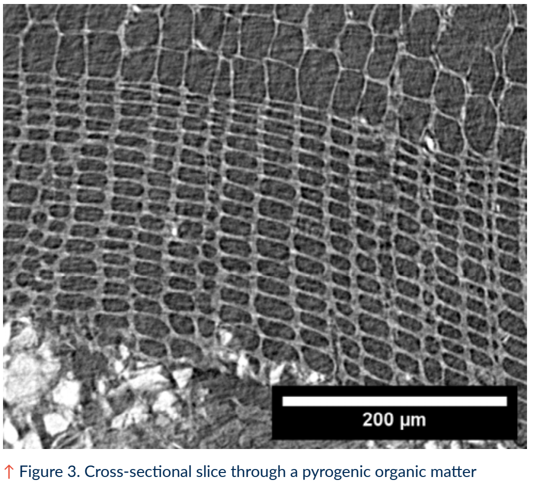
← Figure 1. Photograph of a bentonite sample holder used in an in-situ wetting experiment (left) and its schematics (right).



↑ Figure 2. X-ray radiograph of a bentonite sample (top) and partial densities of water and bentonite clay in it at one instant of time (bottom).

MICROSTRUCTURE OF PYROGENIC ORGANIC MATTER AGED IN FOREST SOIL

Pyrogenic organic matter (PyOM) is formed in wildfires and prescribed burnings or is produced and spread intentionally for soil amendment purposes [2]. It has an important role as a soil enhancer and is expected to deposit carbon in the soil for long periods of time. The properties of PyOM are usually determined from fresh samples, but a few natural analogues exist, too. In our work, we studied one such analogue by using PyOM originating from prescribed burning events aged between 1 and 71 years, to study changes in the PyOM microstructure in the decadal timescale. Extensive X-ray microtomographic imaging showed that PyOM retains its porous structure very well, and the largest structural changes occur on the surface of the PyOM particles in the form of coating layers, pore fillings, and fractures. Figure 3 shows a tomographic cross-sectional slice through a PyOM particle originating from a prescribed burning done during 1948. The original cellular structure of the wood tissue is still well distinguishable, although mineral grains have entered some pores and coated the surface of the particle. This is an indication of high stability of PyOM in the soil.



↑ Figure 3. Cross-sectional slice through a pyrogenic organic matter particle from a prescribed burning conducted in 1948. Despite the age of the particle, its microstructure resembles that of newly burnt wood.

Selected publications

[1] Tero Harjupatana, Arttu Miettinen, Markku Kataja. A method for measuring wetting and swelling of bentonite using X-ray imaging. Applied Clay Science 221, 2022. https://doi.org/10.1016/j.clay.2022.106485

[2] Jari Hyväluoma, Arttu Miettinen, Riikka Keskinen, Kimmo Rasa, Henrik Lindberg. Structural and chemical changes of pyrogenic organic matter aged in boreal forest soil. Pedosphere, 2022. https://doi.org/10.1016/j.pedsph.2022.06.058

COMPUTATIONAL NANOSCIENCE

Professor Hannu Häkkinen

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

1. How does clustering of organic molecules initiate the formation of aerosol particles?

2. How do metal nanoparticles work as thermocatalysts and electrocatalysts?

3. How do gold-based nanoparticles work as sensors in a biological environment?

4. How do gold-based nanoparticles work as targeted carriers for cancer drugs?

https://www.jyu.fi/en/research-groups/computational-nanoscience

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

In 2022, our group enlarged the application range of machine learning methods to two new areas, namely atmospheric chemistry and electrocatalysis, due to two new Academy-funded projects. A new collaboration with the C2CMI institute (*https://www.carbon-2-metal-institute.queensu.ca*) took off due to significant funding granted to the institute in the fall of 2021 by the Canadian government, with JYU being a funded international partner in a six-year program.

USING MACHINE LEARNING TO ACCELERATE CALCULATIONS FOR ATMOSPHERIC CHEMISTRY

A large fraction of atmospheric aerosol particles is formed in the air by condensing organic vapors. Aerosol particles can further grow to form cloud condensation nuclei. Aerosol particles containing different types of organic molecules have varying efficiencies of forming cloud droplets. A new machine learning model developed in our group streamlines the calculation of accurate thermodynamic properties, such as chemical potential, of atmospheric organic aerosol constituents. [1] With the model, properties of new compounds can be calculated faster than before. These properties can be further utilized in global climate models to predict the effects of aerosol particles on climate change.

ENGINEERING NOVEL METAMATERIALS FROM ATOMICALLY PRECISE GOLD CLUSTERS

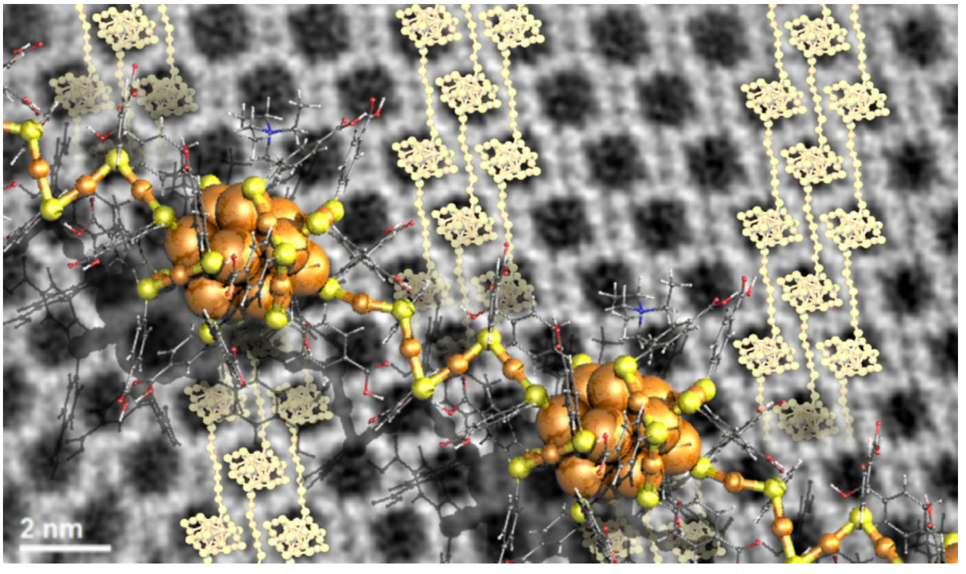
Ordinary solid matter consists of atoms organized in a crystal lattice. The chemical character of the atoms and lattice symmetry define the properties of the matter, for instance, whether it is a metal, a semiconductor or an electric insulator. The lattice symmetry may be changed by ambient conditions such as temperature or high pressure, which can induce structural transitions and transform even an electric insulator to an electric conductor, that is, a metal. Larger identical entities such as nanoparticles or atomically precise metal nanoclusters can also organize into a crystal lattice, to form so called metamaterials. However, information on how to engineer the growth of such materials from their building blocks has been scarce since the crystal growth is a typical self-assembling process.

Our collaborators at the National University of Singapore succeeded in synthesizing macroscopic samples of materials made out of gold clusters consisting of only 25 gold atoms. The morphology of the crystalline material was studied using high-resolution electron microscopy. Our group applied image-processing methods, density functional theory calculations and molecular dynamics simulations to analyze the experimental imaging data to come up with an atomistic model of the material. We proposed that it consists of polymeric chains of clusters with four-gold-atom interparticle links (Figure 2). The work also proposes a new strategy to fabricate novel metal cluster -based metamaterials for investigations of their electronic and optical properties. [2]

Selected publications

[1] N. Hyttinen, A. Pihlajamäki and H. Häkkinen, "Machine Learning for Predicting Chemical Potentials of Multifunctional Organic Compounds in Atmospherically Relevant Solutions," J. Phys. Chem. Lett. 13, 9928 (2022).

[2] Q. Yao, L. Liu, S. Malola, M. Ge, H. Xu, Z. Wu, T. Chen, Y. Cao, M. F. Matus, A. Pihlajamäki, Y. Han, H. Häkkinen and J Xie, "Surface Dynamics Promoted Supercrystal Engineering of Atomically Precise Gold Nanoparticles," Nature Chem. 15, 230 (2023).



↑ Figure 2. Electron microscopy image (background) of an ordered crystal consisting of 25-atom gold clusters. The data could be interpreted by a model of tightly packed polymeric chains of the clusters (light spheres). A close-up visualization of two such clusters, connected by a gold-ligand chain is shown in front. Graphics: Sami Malola.

CONDENSED MATTER THEORY

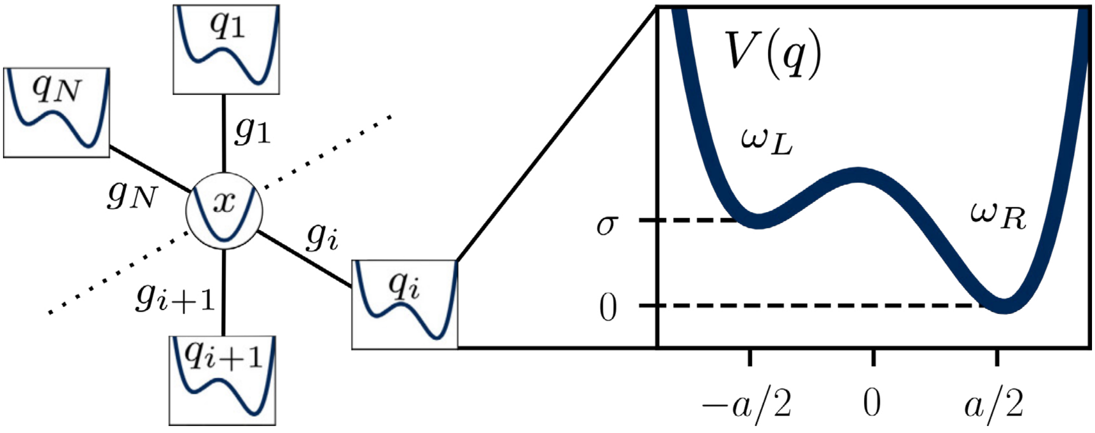
Professor Tero Heikkilä

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

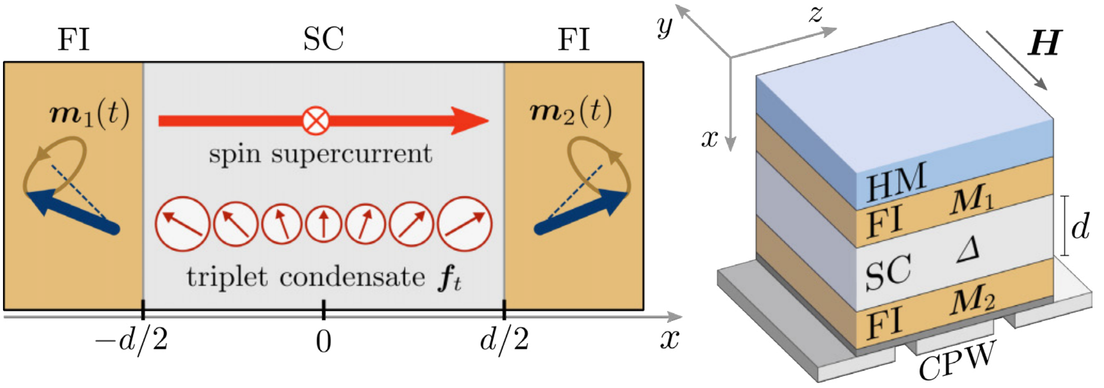
https://www.jyu.fi/en/research-groups/condensed-matter-theory-group

CAVITY-INDUCED BIFURCATION IN CLASSICAL RATE THEORY

Microscopic degrees of freedom, such as molecular vibrations, can couple to external electric fields via a dipole moment. We show that when a system composed of many such microscopic components is placed inside an electromagnetic cavity, the coupling via the cavity field can lead to collective effects [1]. Below a certain critical temperature which depends linearly on the number of molecules, a phase transition related to that in the Ising model occurs, and multiple steady states can exist. These results can have implications for understanding possible effects of cavity fields on chemical reactions, and also describe other systems such as electric circuits and cold atoms in optical traps.



↑ Figure 1. Interactions mediated by a cavity mode x between microscopic modes q.



↑ Figure 2. Proposal for a ferromagnetic resonance experiment to demonstrate spin supercurrents.

LONG-DISTANCE SPIN SUPERCURRENTS

Superconductors can carry not only charge current, but also spin currents between magnets to relatively long distances without producing excess heat, as demonstrated in our work [2]. This is in contrast with ordinary conductors where such frictionless spin currents vanish within atomic distances. However, such currents can be elusive since they do not produce electric signals that could be easily measured. We explain the experimental signatures that indicate their presence, such as changes in the magnetic configuration or the modifications in the magnetic dynamical response in ferromagnetic resonance experiments.

TRANSPORT IN SPIN-ORBIT COUPLED SUPERCONDUCTORS

The spin-orbit interaction in condensed-matter physics is sometimes loosely thought of as an effective magnetic field that has a different sign for spin-up and spin-down electrons. We have studied the transport of electrons in the presence of the spin-orbit coupling (SOC) in diffusive superconducting metals, where impurity scattering randomizes their motion. The diffusive motion of electrons in a real magnetic field can be described with a field theory developed for understanding the quantum Hall effect. In our work [3] we show that a generalization of this theory also describes the spin-Hall effect that arises from the effective magnetic field of the spin-orbit interaction, showing in what sense the analogy is quantitatively correct. We have also investigated the light-matter coupling resulting from the SOC and how it leads to chiral selectivity of absorption [4] in the superconducting state.

SUPERCONDUCTOR-FERROMAGNET HYBRIDS FOR NON-RECIPROCAL ELECTRONICS AND DETECTORS

Hybrid thin films of superconductors and ferromagnets can be used to create non-reciprocal electronic components and self-biased detectors of electromagnetic radiation. We have explored the properties of superconducting diodes made from such elements, [5,6] both theoretically and experimentally. Their natural range of operation temperatures is favorable for several quantum technologies, and they are a crucial component in our SUPERTED FET Open project that makes use of them for electromagnetic radiation detection.

Selected publications

[1] Kalle S. U. Kansanen, Tero T. Heikkilä, “Cavity-induced bifurcation in classical rate theory”, arXiv:2202.12182v3 (2022).

[2] R. Ojajärvi, F.S. Bergeret, M.A. Silaev, and T. T. Heikkilä, "Dynamics of Two Ferromagnetic Insulators Coupled by Superconducting Spin Current", Phys. Rev. Lett. 128, 167701 (2022).

[3] P. Virtanen, F. S. Bergeret, and I. V. Tokatly, “Nonlinear σ-model for disordered systems with intrinsic spin-orbit coupling”, Phys. Rev. B 105, 224517 (2022).

[4] Yao Lu, P. Virtanen, and Tero T. Heikkilä, “Directly probing the chirality of Majorana edge states”, Phys. Rev. B 106, 045139 (2022).

[5] Stefan Ilić, Pauli Virtanen, Tero T. Heikkilä, and F. Sebastián Bergeret, “Current Rectification in Junctions with Spin-Split Superconductors”, Phys. Rev. Applied 17, 034049 (2022).

[6] E. Strambini, et al., “Superconducting spintronic tunnel diode”, Nat. Commun. 13, 2431 (2022).

QUANTUM MANY-BODY THEORY

Professor Robert van Leeuwen

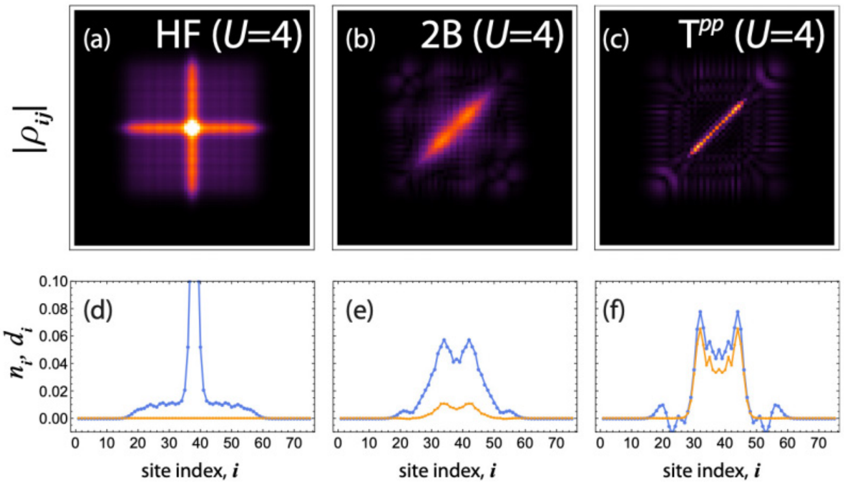
The research of our group focuses on methodological aspects of quantum many-particle theory, notably widening the scope of diagrammatic perturbation theory and density-functional theory with an emphasis on applications to non-equilibrium systems, typically electronic systems exposed to strong external fields.

In recent years there was a strong focus on the study of coupled electron-boson systems and on a deepening of the understanding of several mathematical aspects of the density-functional formalism.

NON-EQUILIBRIUM FORMALISM AND APPLICATION TO THE POLARON-DOUBLON SYSTEMS

In 2022 we continued our long-term project to describe coupled systems of electrons and bosons, such as the description of electron-phonon and electron-photon couplings in solids and electron-vibron coupling in molecules. We developed a very general formalism that can deal with a great variety of interactions between the particles and applied it to the study of the strongly correlated doublon-polaron system.

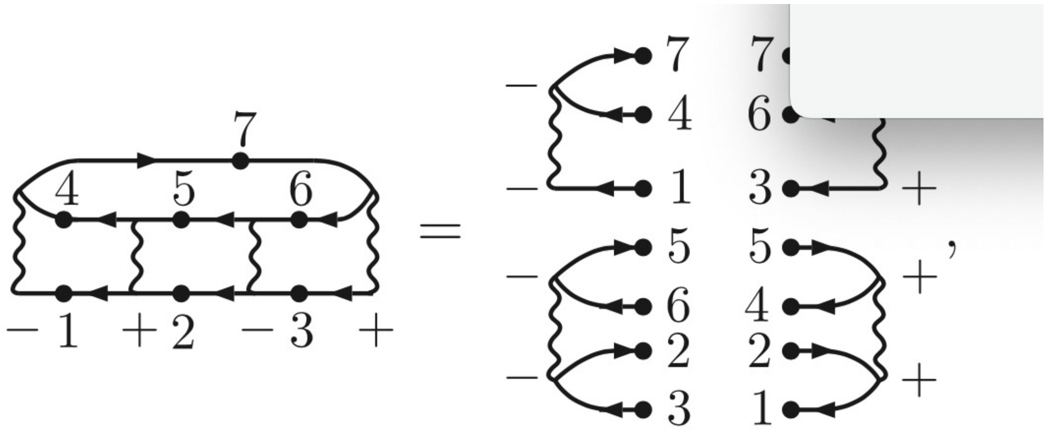
The formalism and the application were published in two extensive back-to-back papers in Physical Review B [1,2]. The key advantage of our formalism, apart from its versatility, is that we showed that it can be implemented in a time-linear fashion thereby greatly reducing the computational effort involved and extending its applicability to realistic electronic systems of current interest.



↑ Figure 1. Temporal snapshots of the time-evolution of a density matrix of a doublon state on a one-dimensional Hubbard lattice, with in the lower panels the corresponding electron and doublon occupations. Left: the mean-field Hartree-Fock case and middle and right: correlated many-body approaches. The most accurate T-matrix approach produces the exact results very well.

SOLUTION OF THE POSITIVITY PROBLEM IN FINITE TEMPERATURE MANY-BODY THEORY

The PhD research of Markku Hyrkäs culminated in the solution [3] of an important open problem in quantum many-body theory, namely, how to ensure the positivity of spectral functions in quantum-many body systems at finite temperature when they are calculated approximately using Feynman diagrams. The issue was solved by us some years ago for the simpler case of many-particle systems at zero temperature, but the problem remained an open issue for many years for the finite temperature case. It required the development of a completely new formalism, namely that of the retarded N-point functions, to solve the issue. With the new formalism in place the solution is very natural and seems almost effortless and it led immediately to a generalization of the result for non-equilibrium systems which are initially prepared in a thermodynamic equilibrium state.



↑ Figure 2. Illustration of a Feynman diagram cutting rule ensuring positivity that fails in the finite temperature case due to the generation of disconnected vacuum diagrams. This issue is resolved in the retarded formulation that we developed in which the vacuum pieces are integrated on a full Keldysh contour and thereby vanish.

Selected publications

[1] Y. Pavlyukh, E.Perfetto, D.Karlsson, R.van Leeuwen, G. Stefanucci, “Time-linear scaling nonequilibrium Green’s function methods for real-time simulations of interacting electrons and bosons. I: Formalism”, *Phys.Rev. B105, 125134 (2022)*

[2] Y. Pavlyukh, E.Perfetto, D.Karlsson, R.van Leeuwen, G. Stefanucci, “Time-linear scaling nonequilibrium Green’s function methods for real-time simulations of interacting electrons and bosons. II. Dynamics of polarons and doublons, *Phys.Rev.B105, 125135 (2022)*

[3] M.Hyrkäs, D.Karlsson, R.van Leeuwen, “Cutting rules and positivity in finite temperature many-body theory”, J.Phys.A: Math. Theor. 55, 335301 (2022)

LOW-DIMENSIONAL NANOMATERIALS MODELING

Professor Pekka Koskinen

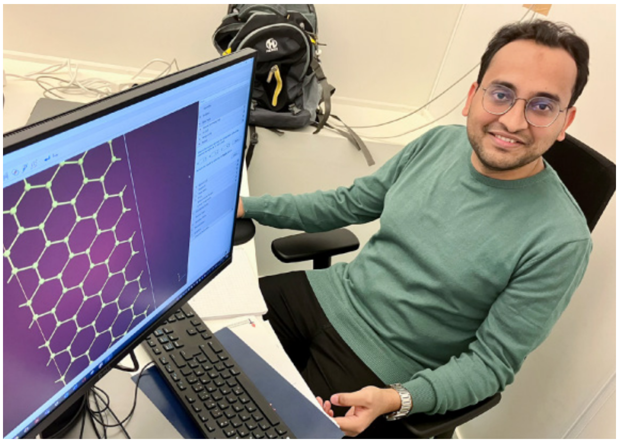
We investigate low-dimensional nanomaterials, especially carbon nanomaterials, for their structural, mechanical, vibrational, electronic, and electromechanical properties using computational methods ranging from continuum to first-principles electronic structure methods.

https://www.jyu.fi/en/research-groups/low-dimensional-nanomaterials-modeling

During 2022 we received 400 k€ funding from Jane and Aatos Erkko foundation for a four-year project *Ecomet: Towards sustainable metal economy: designing interfaces to stabilize two-dimensional metals*. The aim of the project is to design optimally stable two-dimensional metal-carbon interfaces by a computational bottom-up approach, while the overarching goal is to facilitate the experimental preparation of larger and more stable two-dimensional metals.

OPTIMIZING COMPUTATIONAL METHODS FOR TWO-DIMENSIONAL METALS

While experiments on two-dimensional (2D) metals remain scarce, density-functional theory (DFT) provides an ideal approach to predicting their basic properties and assisting their design. However, DFT methods have rarely been benchmarked against metallic bonding at low dimensions. Therefore, we performed a systematic scanning of DFT parameters to optimize computational efficiency. Although today most DFT studies on 2D metals use plane waves, we found that a local basis with the often-used PBE exchange-correlation functional suffices for most 2D metal investigations.[1] In contrast, plane waves and hybrid functionals bring limited improvement compared to the greatly increased computational cost. These results ease the demands for generating DFT data for better interaction with experiments and for data-driven discoveries of 2D metals incorporating machine learning algorithms.



← Figure 1. During 2022 we also began the heavy-duty use of a new computational tool, the QuantumATK atomistic simulation platform. Doctoral student Kameyab Raza Abidi at his desk presenting the features in the software.

Selected publications

[1] Optimizing density-functional simulations for two-dimensional metals, *Kameyab Raza Abidi and Pekka Koskinen*, Physical Review Materials **6**, 124004 (2022)

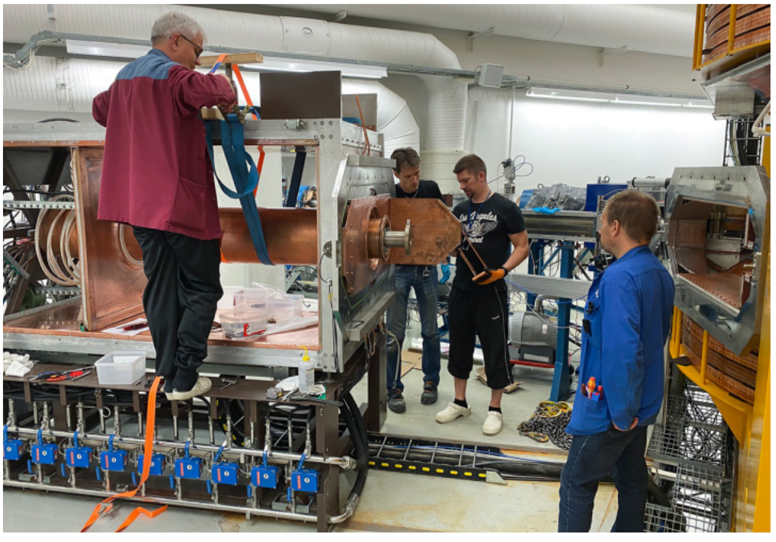
ACCELERATOR LABORATORY

Professor Paul Greenlees
Head of Accelerator Laboratory

After the turmoil caused by the COVID-19 pandemic in 2020 and 2021, it was a relief that in 2022 the operations of JYFL-ACCLAB began to return to something similar to pre-COVID times. Through the course of 2022, the number of scientists visiting the laboratory for experiments began to climb, meetings could again be held face-to-face rather than remotely and the fear of infection began to reside. However, as described later, the effects of COVID-19 were still evident.

The year 2022 was also a special one in the history of the laboratory. At 14:20 28th January, it was exactly 30 years since the first beam was extracted from the K130 cyclotron in 1992 (He^+ ions at 6 MeV/u). Throughout 1992 several other milestones were reached, such as the first extraction of heavy ions on May 14th (Ar^{10+} at 6 MeV/u) and acceleration of protons to 70MeV on June 25th. In addition, it was 15 years since the installation of the 1.7MV Pelletron accelerator in the laboratory. The 30th anniversary of beam from the K130 cyclotron and 15 years of Pelletron research was thus a good excuse for a celebration, more on that later.

In 2022, the K130 cyclotron delivered 5978 hours of beam to experiments, with the average per year from 1996 onwards being 6420 hours. A total of close to 50 different "runs" were carried out, mainly distributed between Nuclear Spectroscopy (36%), RADEF and industrial applications (32%) and IGISOL (32%). Once again, the reliability of the K130 and Pelletron accelerators, ion sources and control system of JYFL-ACCLAB were at an exceptionally high level. In order to try to maintain this level of reliability, our 30-year old must occasionally have pre-emptive maintenance carried out, which is preferable to simply reacting to problems when they occur. In 2022, a total of roughly seven weeks were allocated to maintenance breaks, five of which were scheduled from mid-July to mid-August. The main goal of this extended break was to refurbish one of the RF cabinets, including all the copper tubing for cooling water and many other improvements to the system. The maintenance work began very well, but then the technical team was ravaged by a COVID-19 outbreak and work slowed somewhat. There were also some unseen difficulties which required attention, which resulted in the maintenance break having to be extended by a couple of weeks in order to complete all tasks. Once again, quite incredible work from our excellent technical team in order to achieve this demanding task in such a short time. Some of them can be seen working on the RF cabinet in the photo below. Their work is critical to the success of the laboratory and we are eternally grateful for their fantastic efforts.



← Figure 1. Photo of technical team working on refurbishing one of the K130 RF cabinets.

The year also saw some changes in the permanent staff of these teams and also in the research staff. In the mechanical workshop, Tuomas Pietikäinen left his position and was replaced by Vihtori Pusa and Markus Liimatainen left the control group to pursue new challenges. The Ion Source research group was strengthened by the recruitment of Ville Toivanen as a Staff Scientist on a permanent basis. In the Exotic Nuclei and Beams group, Anu Kankainen was named as a Full Professor from the beginning of the year.

The year also saw a number of new beginnings, positive funding decisions and recognition of the work of JYFL-ACCLAB scientists on several fronts. In January, the first positive funding decision of the year came from the Academy of Finland FIRI (FInnish Research Infrastructure) funding instrument. A total of 1.32M€ was granted by the FIRI panel to fund the procurement of a new 3MV tandem accelerator, to replace the aging 1.7MV Pelletron accelerator used by the Accelerator-Based Materials Research group. The new accelerator will deliver beams with much higher intensities and energies and allow new directions of research to be taken, in line with the JYFL-ACCLAB strategy to increase the number of users, particularly at the national level. Perhaps foremost among these is the possibility to develop a neutron beam which could then be used for research into Boron Neutron Capture Therapy (BNCT), in collaboration with researchers from the Helsinki University Hospital which hosts a dedicated facility for treatment using BNCT.

In September, the latest of the several EU-funded Research Infrastructure access programs that JYFL-ACCLAB participates in began. Known as EURO-LABS (EUROpean Laboratories for Accelerator-Based Science), the program aims to provide support to several communities for access to accelerator facilities. At JYFL-ACCLAB, the EURO-LABS project serves the low-energy Nuclear Physics community, helping to cover the costs for travel of researchers to carry out experiments which are subject to the approval of our international Program Advisory Committee. Further positive news from the Academy of Finland came with the decision to award an Academy Research Fellow position to Kalle Auranen.

A number of our researchers were recognised for their work throughout the year. Mikael Reponen and the IGISOL group, along with theorist Markus Kortelainen, were awarded the University's Scientific Breakthrough prize for their work on the charge radius of ^{96}Ag. Arto Javanainen won the Radiation Effects Early Achievement award of the IEEE Nuclear and Plasma Science Society and Mikko Kivekäs and Akbar Hossain of the Accelerator-Based Materials Research group both won best poster prizes at conferences (Akbar actually twice!).

The fruitful collaboration between JYFL-ACCLAB and the French scientific community was recognised and further formalised in 2022. On 29th March, we are very happy to host the French Ambassador to Finland Agnès Cukierman and the Director of the Institut Français Stéphane Schorderet. JYFL-ACCLAB collaborates with a number of French institutions and has several cotutelle agreements in place. Collaboration with the French laboratory GANIL was formalised with the signing of a bi-lateral agreement between the laboratories at the opening of a workshop dedicated to the MORA experiment on 2nd May. The agreement allows for use of funding to support transfer of knowledge and personnel between France and Finland, in both directions.

Of course one cannot reminisce about the events of 2022 without mention of the Russian attack on Ukraine on 24th February. The reaction of the scientific community was unprecedented, resulting in the cutting of ties with Russian researchers working in Russian institutions. For JYFL-ACCLAB, the biggest effect was on the work of the Nuclear Reactions group, which has had long-standing collaborations with Russian scientists since the early days of the laboratory. Further consequences come from the large Russian contribution to the FAIR facility, the extent of which are still in some part unknown. The war in Ukraine has had a considerable knock-on effect on energy prices, which are a considerable concern for accelerator facilities across Europe. JYFL-ACCLAB was prepared to shutdown operations if necessary, but in writing this text in 2023, the fears of extremely high electricity prices were largely unrealized in Finland.

On a brighter note, JYFL-ACCLAB was very happy to host a three-day set of workshops in August with the possibility of in-person participation, after the disruption of COVID-19. The first of these was a meeting of our International Advisory Board, followed by a Users Meeting and ending with a celebration of 30 years of K130 and 15 years of Pelletron research on 25th August. The program of the day included the main characters from the history of the laboratory: Juha Äystö, Pauli Heikkinen, Rauno Julin, Ari Virtanen and Hannu Koivisto and was attended by a large number of alumni and former staff of the laboratory. In the evening, there was a cruise to Savutuvan Apaja and dinner.

↑ Figure 2. Photos of the staff and guests enjoying the 30/15 celebration event.

NUCLEAR SPECTROSCOPY

Professor Paul Greenlees
Senior Lecturer Panu Ruotsalainen
Senior Researcher Janne Pakarinen
Academy Research Fellow Kalle Auranen
Doctoral Student Henna Joukainen

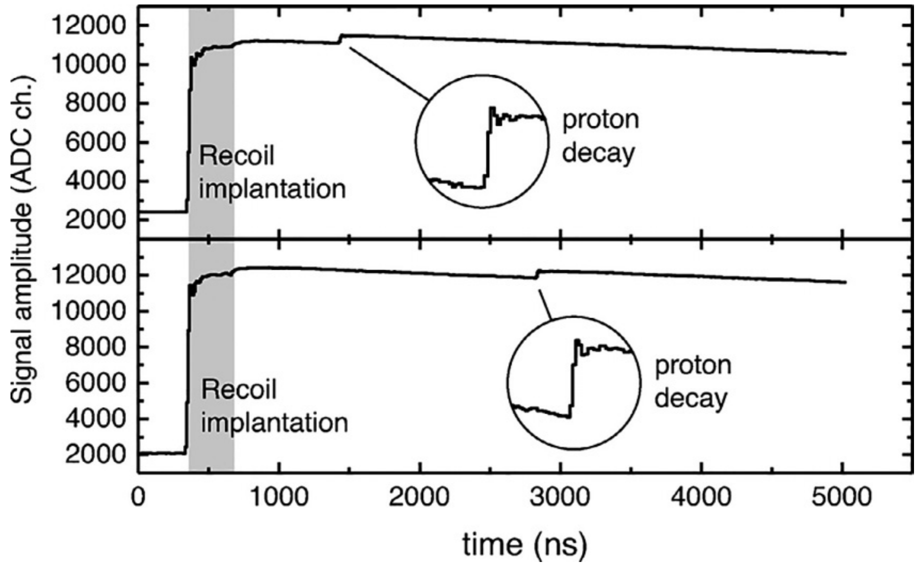
The main activities of the Nuclear Spectroscopy group are related to using in-beam gamma-ray and electron as well as decay-spectroscopic methods to examine the structure of the nucleus through studies of exotic nuclei, mainly along the proton drip line and in the region of heavy elements. The group is also active in international collaborations such as Miniball and the ISOLDE Decay Station at ISOLDE, CERN, in the AGATA collaboration to build a gamma-ray tracking array and in the SUPER-FRS, HISPEC/DESPEC and SHE collaborations which form part of the NuSTAR pillar of FAIR in Germany.

https://www.jyu.fi/en/research-groups/nuclear-spectroscopy-group

The group activities in 2022 included research and development of new scientific instruments and a diverse program of experiments using beams from the K130 accelerator. The experiments totalled 99 days of beam on target in 11 different measurements and the group members were co-authors in 24 peer-reviewed journal publications. As the JUROGAM 3 array was stripped down to 15 Ge detectors whilst the Clover detectors are in use at IJCLab Orsay, our prime focus was on focal-plane decay studies. After a few years of hibernation, the RITU separator was back in action and recommissioned with a new focal-plane set-up developed in-house and stemming from the one designed for the MARA separator. The commissioning of the APPA plunger device paved the way for plunger lifetime measurements using the JYTube charged-particle array for reaction channel selection. Alvaro Tolosa-Delgado and Andres Illana-Sison left the group for new challenges at CERN and at Complutense University of Madrid, respectively, whereas Janne Pakarinen was on a long-term visit at ISOLDE, CERN for the first half of 2022. Our long-term collaborative personnel exchange with the University of Liverpool continued with Joonas Ojala starting there as a post-doctoral research associate in April and Jorge Romero returning to complete his dual-doctorate studies in September. Some of the research highlights from 2022 are discussed below.

DISCOVERY OF PUMPKIN SHAPED ^{149}LU NUCLEUS THAT RADIATES PROTONS WITH RECORD SETTING RATE

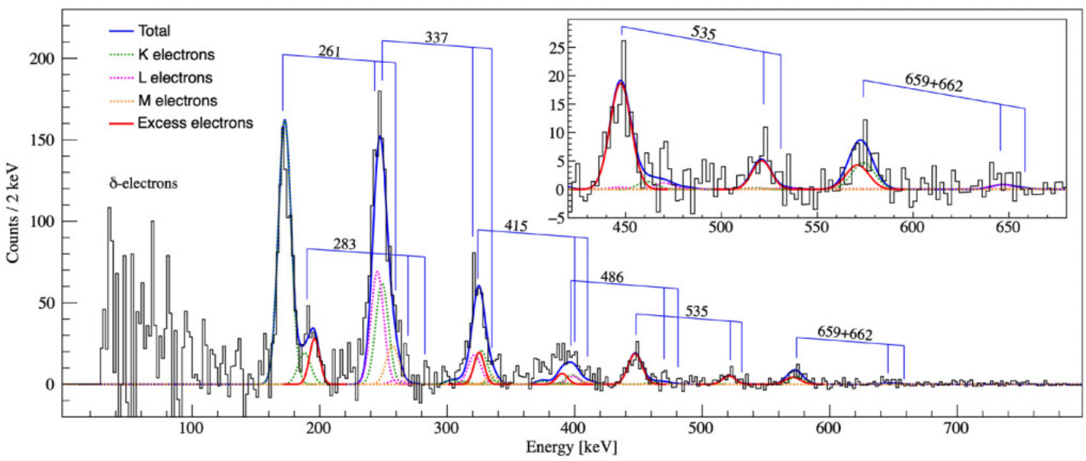
A new atomic nucleus ^{149}Lu, consisting of 71 protons and 78 neutrons, has been synthesized in the fusion of a ^{58}Ni beam and ^{96}Ru target atoms at the MARA separator. ^{149}Lu was found to decay into ^{148}Yb via spontaneous proton emission, and its decay properties turned out to be exceptional; it has the highest decay energy and the shortest directly measured half-life of any ground-state proton emitter known to date. Observation of the swift decay was made possible by modern digital signal processing that allows signal traces to be recorded as shown in Figure 1. Based on theoretical calculations, it was found to be the most oblate deformed (“pumpkin shaped”) proton emitter. This is the first instance when the models of proton emission are tested against such a strong oblate deformation. These observations will help to develop the theory of proton emission as well as the atomic mass models for the most exotic isotopes, both of which are needed to understand the origin of the elements. The results of this study have been published as an Editors’ Suggestion in Physical Review Letters, and were selected as the research highlight of the week by Nature Magazine.



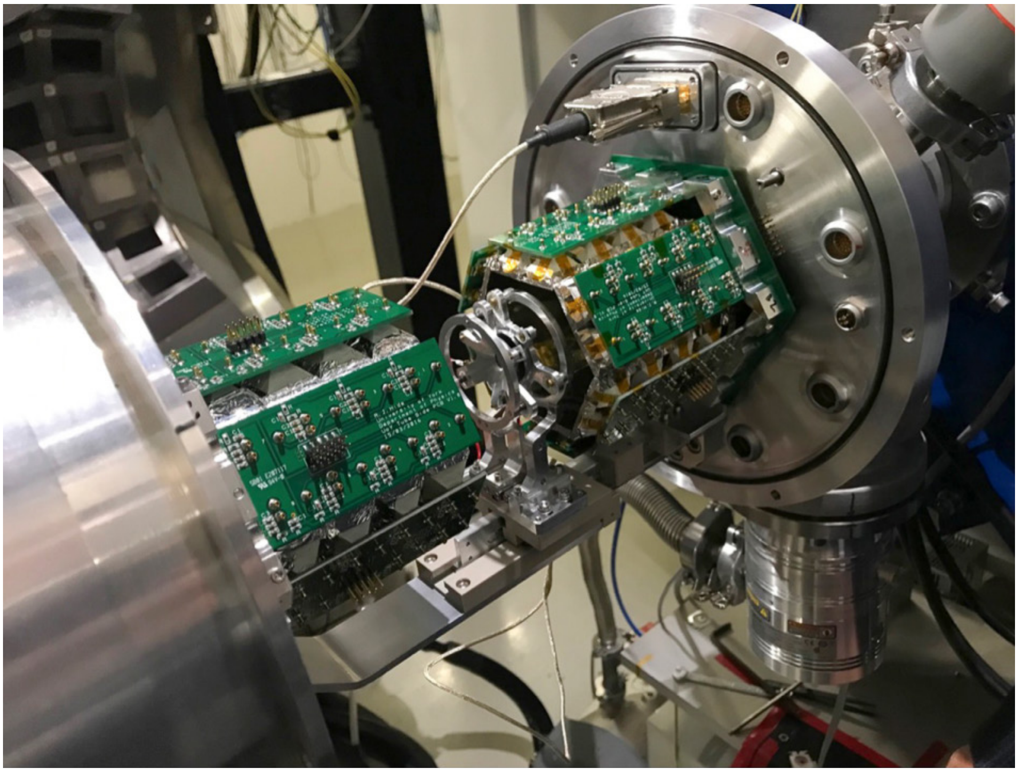
↑ Figure 1. Two examples of a signal trace recorded for the fast proton decay of ^{149}Lu.
Adapted from Phys. Rev. Lett. **128**, 112501 (2022).

REASSIGNING THE SHAPES OF THE EXCITED 0⁺ STATES IN THE ^{186}PB NUCLEUS

The ^{186}Pb nucleus is arguably the most famous nucleus exhibiting shape coexistence. It is the only known system where three different shapes appear as the three lowest states in energy, stimulating broad interest across different physics domains. Our in-beam spectroscopic study using the SAGE spectrometer at the RITU separator sheds light on the competing structures in this unique nucleus. The results redraw the picture of the low-lying states in ^{186}Pb and provide new insight to the quantum laboratory at the heart of triple shape coexistence. The work demonstrated that simultaneous in-beam gamma-ray and electron spectroscopy provides unrivalled sensitivity to probe the electric monopole *(E0)* transitions in nuclei. As shown in Figure 2, careful deconvolution of the peaks allowed the level of excess intensity of electrons to be determined, which is assigned to *E0* transitions in ^{186}Pb. The results called into question previous assignments of the low-lying states in ^{186}Pb and were published by Joonas Ojala *et al*. in a Nature portfolio journal Communications Physics and selected as an Editor's highlight.



↑ Figure 2. Recoil-gated, α-tagged background-subtracted electron energy spectrum obtained for ^{186}Pb. Adapted from Commun. Phys. **5**, 213 (2022).



↑ Figure 3: The Advanced Plunger-Particle detector Array APPA in the MARA beam line.

APPA – INCREASING SENSITIVITY FOR LIFETIME MEASUREMENTS AT THE JYFL RECOIL SEPARATORS

A device known as the Advanced Plunger-Particle detector Array (APPA) was designed and built in collaboration with researchers from the University of Cologne, Germany. The APPA device (see Figure 3) combines a compact Cologne plunger with the JYTube charged-particle detector array and is used in conjunction with the JYFL recoil separators and the JUROGAM 3 array. APPA has been specifically developed for lifetime measurements of the excited states in *N=Z* nuclei. In these experiments, a charged-particle veto can provide unparalleled sensitivity in the selection of the reaction channel of interest. Of particular interest is a measurement of the lifetime of the *T*=1, 2^+ state in the *N=Z* nucleus ^{66}As and of the corresponding state in ^{62}Ga to assess the isospin symmetry breaking effects within isobaric triplets.

APPA was successfully commissioned in-beam in May 2022 during a 4-day test beam time using ^{40}Ca+^{24}Mg and ^{40}Ca+^{28}Si reactions at MARA+JUROGAM 3. Several important aspects, such as the MARA transmission efficiency, charged-particle detection efficiency and performance of the ^{28}Si targets, were assessed. These provided critically important information in preparation for the extremely demanding measurement of ^{66}As.

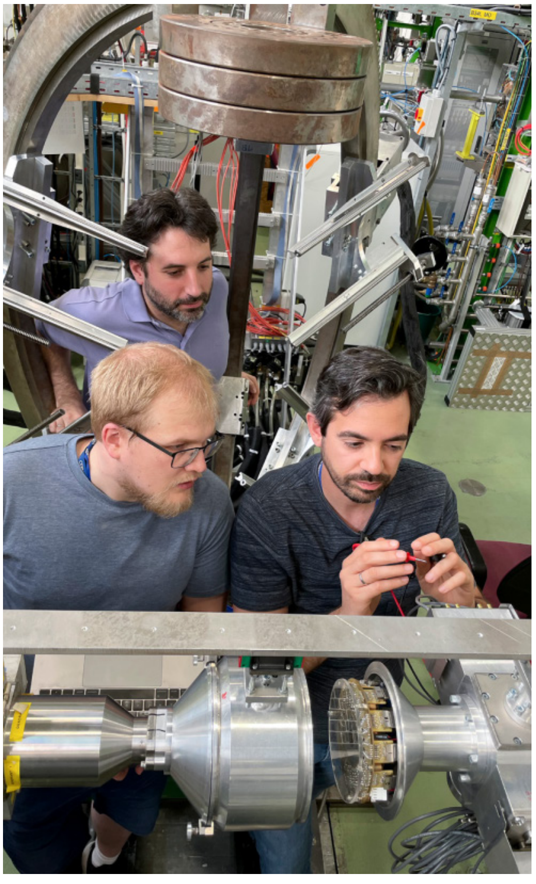
The correct plunger operation was verified with a measurement of the lifetime of the 2^+ state in ^{62}Zn, obtained through several target-to-degrader distances.

APPA is not only limited to the studies of *N=Z* nuclei. After the commissioning run, it was used without the charged-particle array to measure lifetimes of the excited states in the ^{222}Th nucleus employing the charge-plunger technique. Moreover, a plunger campaign using APPA at RITU to measure lifetimes of the excited states in ^{165}, ^{167}Os, ^{190}Pb and ^{192}Po is planned for the first half of 2023. Consequently, JUROGAM 3 was moved at the end of 2022 from MARA to RITU in fully operational mode using the recently built rail system.

SPEDE SPECTROMETER EMPLOYED FOR THE FIRST TIME IN A RADIOACTIVE BEAM EXPERIMENT

In order to understand diverse phenomena in atomic nuclei, a versatile set of tools, techniques and methods are needed. In an ideal case, a number of these could be employed simultaneously in a single experiment. Such an approach not only allows for more efficient use of beam times, but also provides different perspectives for the case of interest and prospects to obtain complementary information.

An important milestone was reached at the end of the 2022 HIE-ISOLDE campaign when the SPEDE spectrometer was employed, for the first time, in a radioactive beam experiment, see Figure 4. This achievement resulted from years of research and development work conducted in the University of Jyväskylä, Finland, in close collaboration with the University of Liverpool, UK. SPEDE introduces a novel concept that allows for direct measurement of conversion electrons from radioactive nuclei without the use of transporting magnetic fields, a development which enables kinematic correction of electrons emitted in flight. The neutron-midshell nucleus ^{182}Hg was studied in a Coulomb excitation experiment. The competing structures associated with different shapes give rise to E0 transitions between states with same spin and parity, rendering observation of conversion electrons important. The successful commissioning of SPEDE in real experimental conditions can be considered as a new opening for future campaigns and is likely to attract more experimental proposals.



↑ Figure 4. Andres Illana (back), Joonas Ojala (front left) and Philippos Papadakis (front right) installing the SPEDE spectrometer in the Miniball beam line at HIE-ISOLDE, CERN

TUIKE – NEW TWINKLING INSTRUMENT FOR FOCAL-PLANE STUDIES

While the position-sensitive plastic scintillator detector Tuike was already taken into use during the summer of 2020, it was only in early 2022 that the properties and features of the detector were published. Tuike is used to detect beta radiation at the focal plane of the recoil separators RITU and MARA, with its main use being in the Recoil-Beta Tagging method. Traditionally, other kinds of decay processes have been used to tag the nuclei of interest, as it has been easier to use the precise energies of, for example, alpha or isomeric decays to identify the nuclei arriving at the focal plane. However, some beta-decaying nuclei have favourable properties such that they decay rapidly and have particularly high beta end-point energies, making it possible to differentiate these events from the general beta background. While investigating the properties of Tuike, it was also noticed that the detector can also be used as an efficient punch-through detector. By the end of 2022, Tuike had been used in five different experiments and the APPA commissioning run.

RESEARCH AT FAIR AND ELSEWHERE

FAIR is a new accelerator complex under construction in Germany. The group continued their efforts to develop new detectors for the Super-FRS separator-spectrometer, which will serve the very first experiments of FAIR within the NUSTAR collaboration. The major improvement has been done in the performance of the particle-tracking detectors and beam profile monitors together with German and US collaborators.

Along the research theme of shape coexistence, the group was involved in the transition probability measurements in ^{176}Hg and ^{172}Pt utilising Gammasphere at Argonne National Laboratory, US.

Selected publications

Auranen, K., Briscoe, A. D., Ferreira, L. S., Grahn, T., Greenlees, P. T., Herzáň, A., Illana, A., Joss, D. T., Joukainen, H., Julin, R., Jutila, H., Leino, M., Louko, J., Luoma, M., Maglione, E., Ojala, J., Page, R. D., Pakarinen, J., Rahkila, P., . . . Zimba, G. (2022). Nanosecond-Scale Proton Emission from Strongly Oblate-Deformed ^{149}Lu. *Physical Review Letters, 128*(11), Article 112501. *https://doi.org/10.1103/PhysRevLett.128.112501 Open Access*

Joukainen, H., Sarén, J., & Ruotsalainen, P. (2022). Position sensitive plastic scintillator for beta particle detection. *Nuclear Instruments and Methods in Physics Research. Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment*, *1027*, Article 166253. *https://doi.org/10.1016/j.nima.2021.166253 Open Access*

Ojala, J., Pakarinen, J., Papadakis, P., Sorri, J., Sandzelius, M., Cox, D. M., Auranen, K., Badran, H., Davies, P. J., Grahn, T., Greenlees, P. T., Henderson, J., Herzáň, A., Herzberg, R.-D., Hilton, J., Jakobsson, U., Jenkins, D. G., Joss, D. T., Julin, R., . . . Wadsworth, R. (2022). Reassigning the shapes of the 0+ states in the 186Pb nucleus. *Communications physics*, 5, Article 213. *https://doi.org/10.1038/s42005-022-00990-4 Open Access*

Zhang, W., Cederwall, B., Aktas, Ö., Liu, X., Ertoprak, A., Nyberg, A., Auranen, K., Alayed, B., Badran, H., Boston, H., Doncel, M., Forsberg, U., Grahn, T., Greenlees, P. T., Guo, S., Heery, J., Hilton, J., Jenkins, D., Julin, R., . . . Wadsworth, R. (2022). Observation of the proton emitter $^{116}_{57}La_{59}$. *Communications Physics*, 5, Article 285. *https://doi.org/10.1038/s42005-022-01069-w Open Access*

EXOTIC NUCLEI AND BEAMS

Professors Ari Jokinen, Anu Kankainen and Iain Moore

Senior researchers Tommi Eronen and Heikki Penttilä

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

https://www.jyu.fi/en/research-groups/the-exotic-nuclei-and-beams-group

ON-GOING PROJECTS, RESEARCH ACTIVITIES AND NEWS

Our group continues to benefit from a variety of external funding sources. Heikki Penttilä is the local coordinator of two EU EURATOM projects: a Joint Research Activity in SANDA (Supplying Accurate Nuclear Data for Energy and Non-energy Applications) and ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning), a transnational access project providing support for external user experiments at IGISOL. Anu Kankainen leads the European Research Council (ERC) Consolidator Grant project MAIDEN (Masses, Isomers and Decay studies for Elemental Nucleosynthesis). While the Academy Project for MARA-LEB ended in September 2022, the PANTHER project continues in a consortium led by Iain Moore and theorist Markus Kortelainen, focused on advancing our understanding of the actinide elements. We are a beneficiary in the Marie Curie Innovative Training Network, LISA (Laser Ionization and Spectroscopy of Actinides). In addition to the experimental programme at IGISOL, we contribute to the FAIR Phase-0 experiments.

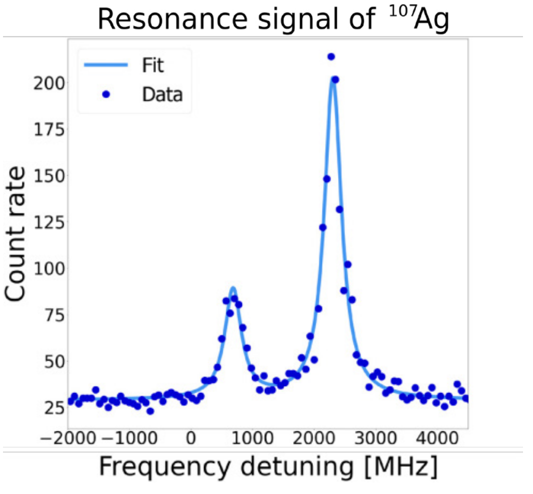
In personnel news, Anu Kankainen started as a full professor on 1st January 2022. Wirunchana (Nin) Rattanasakuldilok started in the group having been the sole awardee of a new Finland Doctoral Fellowship. This four-year PhD studentship is awarded to the best international doctoral students who have been admitted to the doctoral programmes of JYU. Luis Miguel Motilla started as a cotutelle PhD student between U-Caen and JYU for the MORA project. Maxime Mougeot started as a postdoctoral researcher at JYFLTRAP, bringing a wealth of experience from ISOLTRAP. Mikael Reponen was awarded the JYU 2022 Scientific Breakthrough Award with Markus Kortelainen for their research leading to new insights in the nuclear structure below Sn-100. Three of our students received prizes for best posters: Andrea Raggio at the LISA summer school, Sonja Kujanpää for the Euroschool on Exotic Beams, and Lama Al Ayoubi in the H2020-ARIEL "HISPANOS Hands-On school on the production, detection and use of neutron beams".

DEVELOPMENTS

RAPTOR

RAPTOR (Resonance ionization spectroscopy And Purification Traps for Optimized spectRoscopy) is a small-footprint collinear resonance ionization spectroscopy device under commissioning at the IGISOL facility. The device is located directly downstream from the radiofrequency cooler-buncher, on a high-voltage platform that allows for a variable beam energy between 2-10 keV. To fully exploit the capabilities of RAPTOR, it has been designed in such a way that laser-ionized species can be extracted and delivered to JYFLTRAP. This will offer exciting opportunities to combine the element selective capabilities of resonance laser ionization with high-resolution mass separation.

In late 2022, the first high-resolution laser ionization spectroscopy test was successfully carried out using stable Ag-107,109 at beam energies of 2 keV and 5 keV, highlighted in Fig. 1. Isotope shift and hyperfine factors for the first excitation step were compared with literature values and found to be in good agreement. An impressive resolution of ~300 MHz was achieved. The immediate goals will be to extract reliable numbers for neutralization and overall efficiency. Beams will also be delivered soon to JYFLTRAP. Stay tuned for first online results!

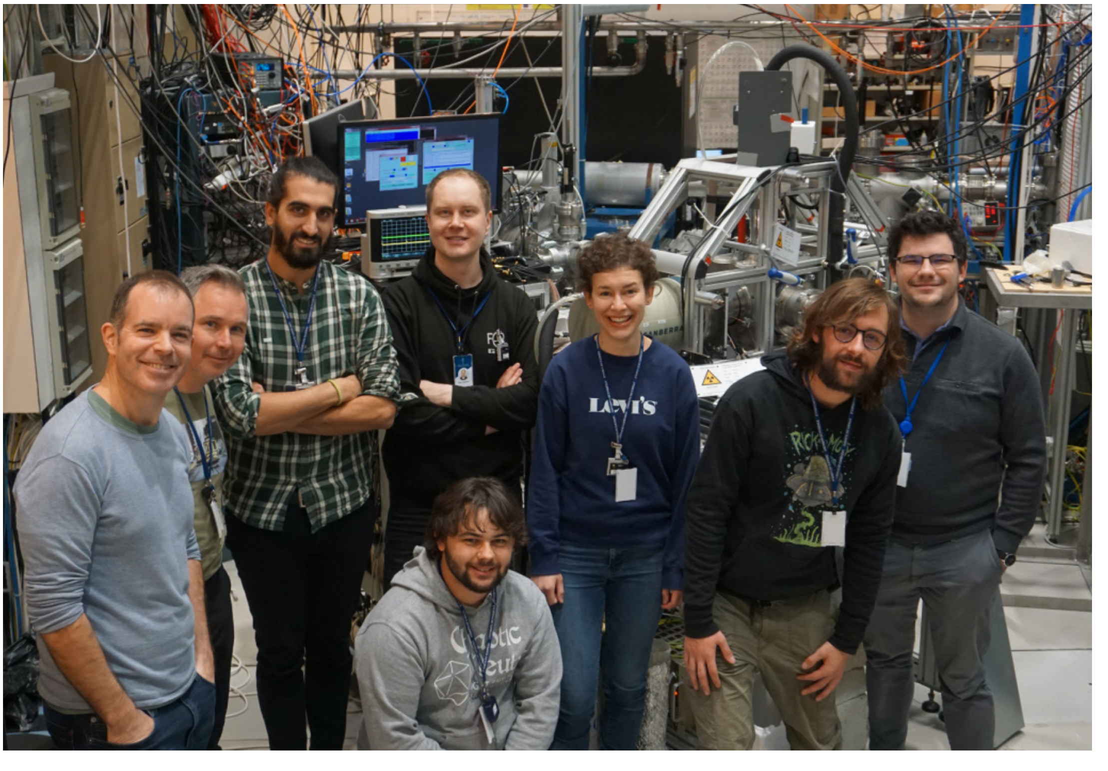


↑ Figure 1. Hyperfine spectrum of Ag-107 with 5-keV beam energy. A resolution of approximately 300 MHz was achieved.

VADER

In collaboration with CEA Saclay, a new decay station has been developed as part of our program for the study of basic nuclear decay properties of neutron-deficient actinide isotopes produced in fusion-evaporation reactions. VADER (Versatile Actinides DEcay spectRoscopy setup) consists of a compact array of silicon detectors, a liquid nitrogen cooled silicon lithium (Si(Li)) detector and three broad energy germanium detectors, placed around a thin carbon foil into which radioactive ions are stopped. The combined use of the different detectors allows the coincident measurement of α decays, de-excitation γ rays and conversion electrons. In November 2022, VADER was commissioned in an experiment with several goals. One focus was on testing Drop-on-Demand U-233 targets developed by the nuclear chemistry research group of Mainz to investigate target durability as well as resulting isotope yields. A second goal was the investigation of basic decay properties of neutron-deficient actinides produced in proton-induced fusion-evaporation of Th-232. This work will provide useful information to explore the possible emergence of reflection asymmetric shapes in the region through the study of nuclear decay schemes.

↓ Figure 2. IGISOL actinide research team together with CEA Saclay collaborators in front of the VADER decay station.



MORA status

The Matter's Origin from RadioActivity experiment (MORA) searches for a signature of CP violation in the nuclear beta decay of radioactive Mg-23 nuclei. In nuclear beta decay, the so-called D correlation violates time reversal, and via the CPT theorem, the CP symmetry. MORA aims at achieving a precision measurement of the D correlation in the decay of Mg-23, thanks to a unique combination of ion trapping and laser polarization techniques.

After installation in late 2021, an intense period of offline activity started the year 2022, followed by 3 short test beam times in February, May and November. These beam times permitted the commissioning of the entire device, gradually improving the performance. A capture efficiency of 10% could be achieved for ions delivered from the RFQ mini-buncher to the MORA trap. A trapping half-life of > 5 s could be achieved, while the latest data suggest that even longer half-lives can be attained when using helium cooling in the trap. This exceeds the trapping half-lives measured with LPCTrap, the ancestor of the MORA trap, by more than an order of magnitude. The proof of principle of the polarization technique in the trap was attempted although the data analysis is complicated due to low statistics and unfavorable signal-to-noise ratio. The biggest challenge is to reduce the stable Na-23 ions in the beam, which limits the number of Mg-23 ions accumulated per bunch in the mini-buncher to a few hundred at most. R&D will be conducted in 2023 to eliminate surface-ionized Na contamination, before resuming data accumulation for the polarization proof-of-principle and the precision D correlation measurement.

RESEARCH HIGHLIGHTS

In the following, selected experimental and publication highlights from 2022 are summarized.

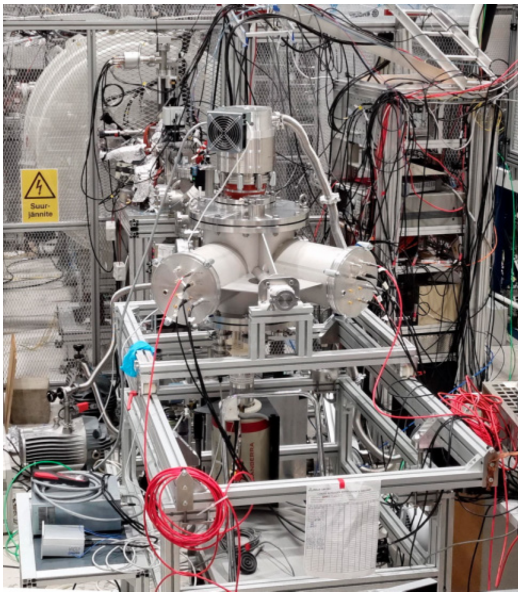
Collinear laser spectroscopy

In 2022, we continued our exploration of refractory proton-rich isotopes with new measurements of the charge radii and electromagnetic moments of iron (Z=26) and cobalt (Z=27) isotopes. These elements have complex atomic/ionic level structures and therefore provide an additional challenge to their study. Indeed, until our work, no radioactive cobalt isotopes had been studied with laser spectroscopy. The region of interest is particularly interesting from the viewpoint of collectivity and charge radii trends across the N=28 shell closure. As one moves towards the N=Z line, the self-conjugate isotopes Co-54 and Fe-52 can be used to study proton-neutron symmetries.
In our recent work, we successfully extracted nuclear structure information on Fe-53-58 as well as Co-54,55,57-59. The latter measurements are an important stepping stone towards an investigation of the proton-emitting isomer in Co-53.

Our collaboration also had important articles published in 2022. We only mention here the study of the impact of nuclear deformation and pairing on the charge radii of palladium isotopes [1].

Trap-assisted beta-decay studies for neutrino physics

How well the measured antineutrino spectrum from reactors is understood has attracted considerable attention in recent years in relation to neutrino oscillation experiments. Measurements of the most relevant decays using the pure beams of IGISOL after the JYFL Penning trap combined with the total absorption technique (TAGS) have contributed to dramatically improving the summation method used for calculating the spectrum. These results have provided complementary evidence that questions the mere existence of the reactor neutrino anomaly. In 2022, the Nantes-Valencia-Surrey-Jyväskylä collaboration performed two new experiments, to further improve the nuclear data required for the summation method. In the first one we installed a new setup to measure the shape of the beta transitions of relevant contributors to the reactor antineutrino spectrum (see Fig. 3). Later in September, a new TAGS experiment was performed. The analysis of those experiments is presently on-going.



↑ Figure 3. The new DE-E spectrometer in place after the JYFLTRAP Pennng trap used in measurements of the shape of the beta spectra from different purified fission fragments.

MR-TOF online mass measurements

The very first mass separation of on-line produced exotic ions was achieved with the multi-reflection time-of-flight (MR-TOF) mass separator at IGISOL in February 2022. The ions were produced in proton-induced fission reactions and mass number A=107 was chosen as one of the isobaric chains to be measured. With the achieved mass resolving power exceeding 10^5, the fission-produced isobars could be readily separated and identified by their mass. The kinetic energy of the ion beam was increased to 2 keV to allow for efficient injection into the MR-TOF and subsequent further transfer, for example, to the JYFLTRAP Penning trap spectrometer. Also, it was necessary to upgrade the radiofrequency amplifier system of the cooler-buncher. Later in the year, the MR-TOF was already used in multiple experiments.

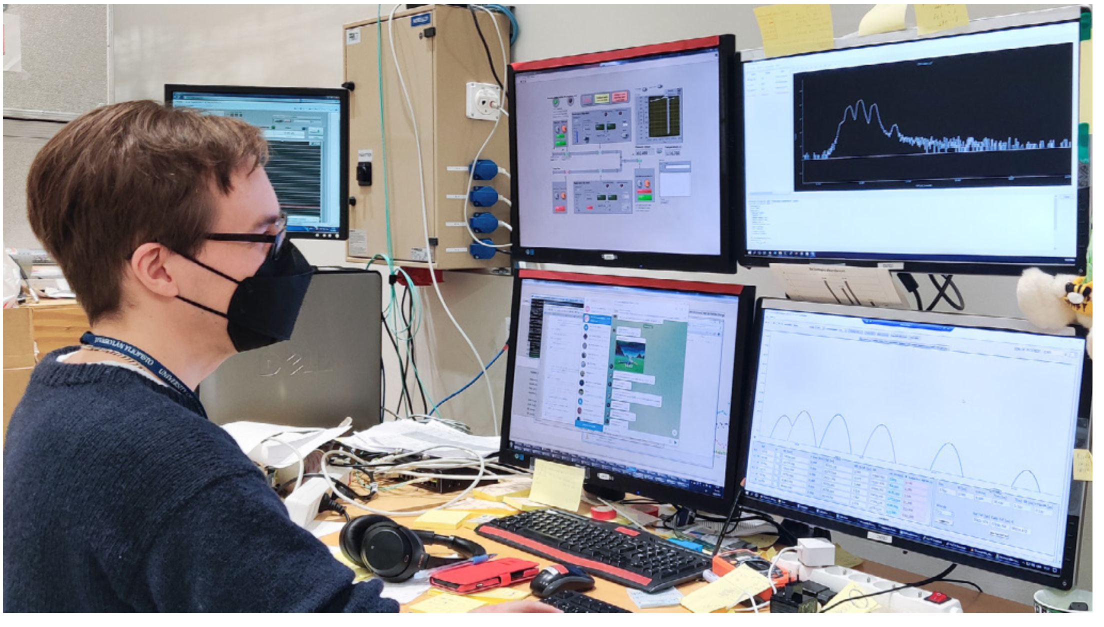
Selected publications

[1] Impact of nuclear deformation and pairing on the charge radii of palladium isotopes, S. Geldhof *et al.*, Phys. Rev. Lett. 128 (2022) 152501. *https://doi.org/10.1103/PhysRevLett.128.152501*

[2] High-precision electron-capture Q value measurement of 111In for electron-neutrino mass determination, Z. Ge, T. Eronen *et al.*, Phys. Lett. B 832 (2022) 137226. *https://doi.org/10.1016/j.physletb.2022.137226*

[3] Mass measurements towards doubly magic 78Ni: Hydrodynamics versus nuclear mass contribution in core-collapse supernovae, Giraud, S., Canete, L., Bastin, B., Kankainen *et al.*, Phys. Lett. B 833 (2022) 137309.*https://doi.org/10.1016/j.physletb.2022.137309*

[4] β- and γ-spectroscopy study of 119Pd and 119Ag, Kurpeta, et al., Phys. Rev. C 105(3) (2022) 034316. *https://doi.org/10.1103/PhysRevC.105.034316*



↑ Figure 4. PhD student Ville Virtanen obtaining the first on-line mass spectrum with the MR-TOF.

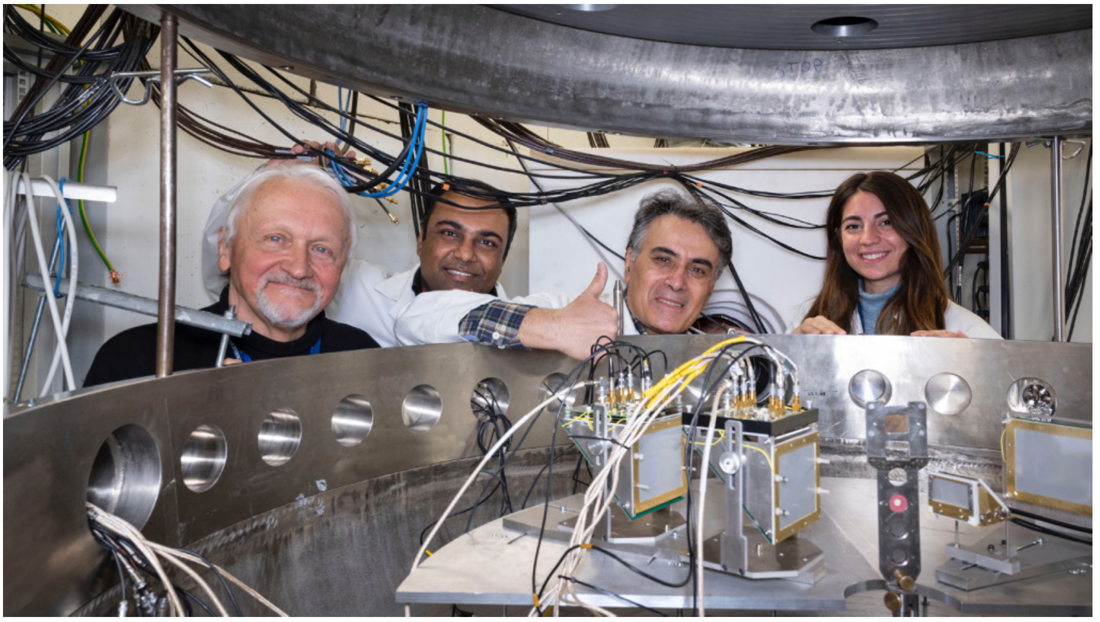
INSTRUMENTS AND METHODS
IN NUCLEAR, PARTICLE, AND ASTROPARTICLE PHYSICS

Senior Researcher Wladyslaw H. Trzaska

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

Nuclear Reaction (NR) studies at JYFL date back to the first beams delivered by the K130 cyclotron. In fact, before the other facilities reached their full research potential around the turn of the century, HENDES was the most prominent international collaboration at AccLab in terms of the number and duration of their visits. Russian teams were an integral part of that effort using up to 1 000 hours of K130 beam per year. Unfortunately, this era of three decades of fruitful cooperation ended abruptly on 24 February 2022 with the barbaric attack of the Russian army on Ukraine. Consequently, our University and the Academy of Finland suspended all joint projects indefinitely, cancelled mobility grants, and forbade co-authoring papers with scientists affiliated with Russian institutions. The common CERN-based activities will continue till the termination of the bilateral agreements at the end of 2024. However, while crediting individuals and providing their ORCID numbers, the publications will omit all Russian affiliations and acknowledgements to their funding agencies.

← Figure 1. Left: expanded LSC cavern. Top right: new beam dump structure. Bottom right: instrumentation for fission studies.



↑ Figure 2. The first LSC experiment after the COVID-19 break. From the left: W.H. Trzaska, T. Banerjee, E. Vardaci, and D. Mercogliano; May 5th, 2022.

These political developments and a slow global recovery from the effects of the COVID-19 pandemic made a noticeable impact on the 2022 NR research at JYFL. On the positive side, we have completed the expansion of the Large Scattering Chamber (LSC) cavern and carried the first measurements there. The significantly enlarged cavern has a higher ceiling, better air exchange, and allows unobstructed LSC access from all sides. An oversized, well-shielded beam dump absorbs beam particles exiting the LSC. It consists of a Faraday Cup with a carbon stopper surrounded by an iron core placed in a hollow 1 m^3 polyethylene (PE) cube. PE is loaded with 5% of boron. The new beam dump significantly reduces the gamma and neutron background in the cavern allowing for measurements with high-intensity light ion beams. All cables between the LSC and the dedicated electronics racks outside the cavern are routed through a chicane in the concrete shielding.

In May 2022, the new cavern was inaugurated by the team from Naples testing an MCP-based detector system in the LSC with a beam cocktail. Thanks to the outstanding commitment and expertise of the AccLab technical team, everything worked flawlessly. This was a noticeable achievement considering that all the services (vacuum, water cooling, power supplies, etc.) had to be cut and reconnected to accomplish this major reconstruction project.

LSC is now ready for proposals and experiments. There is also ample space in the expanded cavern for new experimental setups. Currently, the 0 and +30-degree exit lines from the switching magnet are used for irradiations with low-intensity beams and for time-of-flight-based measurements.

One of HENDES' 2022 highlights was the invitation to deliver a keynote address at NeIC 2022 (*https://indico.neic.no/event/204/page/68-keynotes*). It was the 10th anniversary of the biannual meetings on Nordic Models for Open Science Collaboration. The talk "Quark Matter, Dark Matter, Does it Matter?" illustrated the importance and relevance of basic research and appealed to the representatives of the funding agencies to have more trust in scientists, keep politics out of science and support non-mainstream research as well. Judging by impressive applause, many researchers share that opinion.

Selected publications

[1] E.M. Kozulin, G.N. Knyazheva, I.M. Itkis, M.G. Itkis, Y.S. Mukhamejanov, A.A. Bogachev, K.V. Novikov, V.V. Kirakosyan, D. Kumar, T. Banerjee, M. Cheralu, M. Maiti, R. Prajapat, R. Kumar, G. Sarkar, W.H. Trzaska, A.N. Andreyev, I.M. Harca, A. Mitu, & E. Vardaci (2022). Fission of 180,182,183Hg* and 178Pt* nuclei at intermediate excitation energies. Physical Review C, 105(1), Article 014607. *https://doi.org/10.1103/PhysRevC.105.014607*

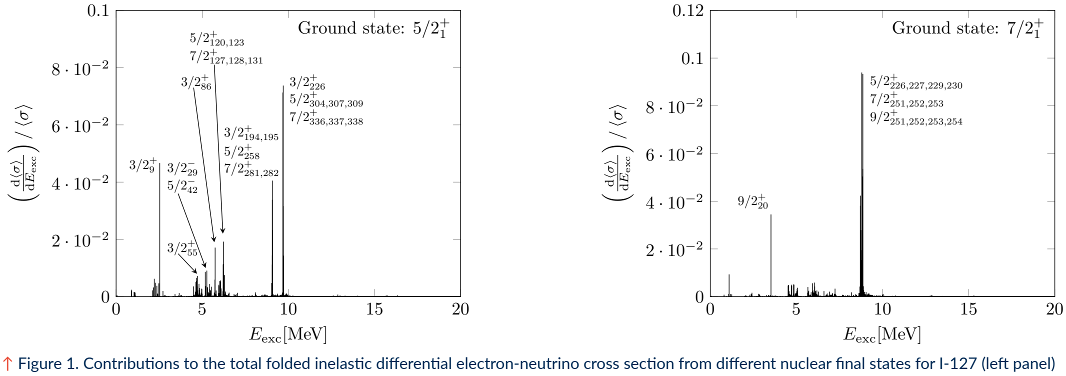
NUCLEAR STRUCTURE AND NUCLEAR PROCESSES

Professor Jouni Suhonen

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

(ANTI)NEUTRINO AND WIMP SCATTERING IN NEUTRINO AND DARK-MATTER TELESCOPES

A large number of the presently running and planned neutrino and dark-matter telescopes use thallium- or sodium-doped cesium-iodide (CsI) or sodium-iodide (NaI) crystals. For that reason it is of interest to compute cross sections for the scattering of (anti)neutrinos and WIMPs (weakly interacting massive particles) off I-127 and Cs-133. In a recent work [1] the cross sections for elastic and inelastic neutral-current (NC) scattering of supernova (anti)neutrinos off these target nuclei were computed. The (anti)neutrino flux from a supernova can be taken into account by folding the bare cross sections with the anticipated energy distributions of different (anti)neutrino flavors. Of particular interest are the contributions of different nuclear final states, excited in the inelastic NC scattering, to the folded cross section. These contributions are shown in figure 1 for the particular case of electron-neutrino scattering off the I and Cs target nuclei. It can be seen that for both target nuclei the leading contributions come from the so-called Gamow-Teller type of transitions where the ground-state spin of the target (5/2+ for I-127 and 7/2+ for Cs-133) is changed by at most one unit. In the figures, the strong peaks above some 8 MeV of excitation can be interpreted as spin-flip M1 giant resonances.



↑ Figure 1. Contributions to the total folded inelastic differential electron-neutrino cross section from different nuclear final states for I-127 (left panel) and Cs-133 (right panel).

Finding new target materials for dark-matter direct detection is a burning issue at present. In the work [2] the potential of the nuclei Sn-119 and Sb-121 for WIMP detection in elastic and inelastic scattering processes in terrestrial dark-matter telescopes was explored. According to the cross-section calculations the elastic channel was quite competitive for both nuclear targets. The inelastic channel, leading to a very low-lying first excited state available in these targets, was found to be significant and worth further investigations for concrete detector developments.

TOWARDS VERSATILE PROBES OF NUCLEAR STRUCTURE FOR NEUTRINOLESS DOUBLE BETA DECAY

Neutrinos are neutral elementary particles of a tiny mass that play a major role in different domains of physics, such as particle and nuclear physics (neutrino oscillations, decays of particles and nuclei, neutrinos from the Earth and nuclear reactors), astrophysics (stellar evolution, neutrinos from the sun and supernovae), cosmology (structure and evolution of the Universe, contributions to dark matter), etc. There are still many unanswered fundamental questions related their properties and behavior, like (a) the basic character of the neutrino (Dirac or Majorana particle), (b) their absolute mass and mass hierarchy (only relative masses can be extracted from the neutrino-oscillation experiments), (c) their role in the violation of the established laws of the Standard Model (SM) of physics, like the lepton-number conservation (d) the mechanism generating their mass, (e) the possible existence of sterile neutrinos. All this makes neutrinos excellent probes of the beyond-the-Standard-Model (BSM) physics which is the current frontier and hot topic of contemporary physics. The significance of neutrinos is highlighted by the myriads of present and planned neutrino-physics experiments underground, above ground and in space.

An ideal probe for the above-listed points (a) - (c) is the so-called neutrinoless double beta decay (0-DBD) of atomic nuclei. All the involved highly expensive experimental investigations need support from complex theoretical studies for the analysis and interpretation of the gained data. In order to proceed, 0-DBD needs a non-zero Majorana mass of the neutrino, and at the same time it generates a lepton-number violation. All this probes the essence of BSM physics. On the nuclear-physics side a reliable nuclear many-body theory is required in order to access the involved nuclear-structure effects, condensed in the so-called nuclear matrix elements (NME). Over the years, these NME have been calculated within numerous nuclear-theory frameworks leading to a wide spread of their values and a confusion in the experimental 0-DBD community. In addition, the uncertain value of the so-called weak axial-vector coupling gA in nuclei adds to the confusion and the solution of the present discrepant situation in nuclear theory has become a first priority in the nuclear many-body community. Concerning the situation with the axial coupling, a recent experimental study of the beta electron spectrum of In-115 [3], assisted by our nuclear-theory group, reported a notably quenched value for gA. This quenched value can also play a role in the determination of the antineutrino flux and its energy distribution in nuclear reactors, as pointed out in our recent theoretical investigation of the total beta spectrum of Rb-92 in [4].

The nuclear-structure aspects of 0-DBD can be probed in computations of the decay rates of the two-neutrino double beta decay (2-DBD), which is a second-order weak process within the SM. Comparing the measured decay rates with the computed ones gives information on the suitability of a nuclear many-body framework for the 0-DBD calculations, as well. In recent works large-scale nuclear-structure calculations were performed to explore the decays of Ge-76 [5] and Xe-136 [6] to excited final states in Se-76 and Ba-136. In the past, the nuclear-structure frameworks have been "calibrated" by exploiting data on the location of the giant Gamow-Teller resonance in the intermediate nucleus of 0-DBD. Lately a new probe has become available: the data on spin-dipole giant resonances in the 0-DBD intermediate nuclei. A survey of the effects of this additional piece of information was done lately in [7]. As a new idea, one can try to extend this kind of comparison to other kinds of spin-multipole giant resonances (SMGR). In [8] it is suggested that measurements of isovector and isoscalar SMGR in the parent and daughter nuclei of doube-beta-decay triplets could be used for this purpose. Further studies of multipole giant resonances without the spin contribution are in progress. In addition, measurements of 0-DBD decay energies (Q-values) for new 0-DBD candidates are planned by the JYFLTRAP experimental collaboration. A good start is the joint experimental and theory effort concerning the 0-DBD decay of Mo-98 [9]. A further probe of the 0-DBD is the ordinary muon capture (OMC). The OMC operates in the same momentum-exchange region as the 0-DBD, and thus constitutes a perfect surrogate process to study nuclear-structure effects in 0-DBD. A long leap forward was taken in [10] by engaging an ab initio model in calculation of the OMC on Mg-24.

Selected references

[1] M. Hellgren and J. Suhonen, Physical Review C 106, 025808 (2022).

[2] J. Kasurinen, J. Suhonen, P. C. Srivastava and P. Pirinen, UNIVERSE 2022, 8, 309.

[3] A. F. Leder et al., Physical Review Letters 129, 232502 (2022).

[4] M. Ramalho et al., Physical Review C 106, 024315 (2022).

[5] J. Kostensalo, J. Suhonen and K. Zuber, Physics Letters B 831, 137170 (2022).

[6] L. Jokiniemi et al., Physics Letters B 838, 137689 (2023).

[7] H. Ejiri, L. Jokiniemi and J. Suhonen, Physical Review C 105, L022501 (2022).

[8] E. Kauppinen and J. Suhonen, Physical Review C 106, 064315 (2022).

[9] D. A. Nesterenko et al., The European Physical Journal A 58:44 (2022).

[10] L. Jokiniemi et al., Physical Review C 107, 014327 (2023).

GLOBAL PROPERTIES OF NUCLEI

Associate professor Markus Kortelainen

Our group develops and applies nuclear structure models, focusing mainly on nuclear density functional theory as a theoretical framework. Our goal is to improve nuclear structure models and their description of nuclei at the global level, throughout the whole nuclear chart. We collaborate with the experimental nuclear physics groups at the JYFL accelerator laboratory, the local nuclear theory group, and many research groups abroad.

https://www.jyu.fi/en/research-groups/global-properties-of-nuclei-group

UNIVERSAL TREND OF CHARGE RADII OF EVEN-EVEN CA-ZN NUCLEI

Radii of nuclear charge distributions carry information about the strong and electromagnetic forces acting inside the atomic nucleus. While the global behavior of nuclear charge radii is governed by the bulk properties of nuclear matter, their local trends are affected by the quantum motion of proton and neutron nuclear constituents. The current data on measured differential charge radii between neutron numbers N = 28 and N = 40 exhibits a universal pattern, independent of the atomic number. In recent work, we have shown that nuclear density functional (DFT) based models and the ab-initio approach can reproduce the smooth rise of differential charge radii and their weak dependence on the atomic number [1], illustrated in fig. 1.

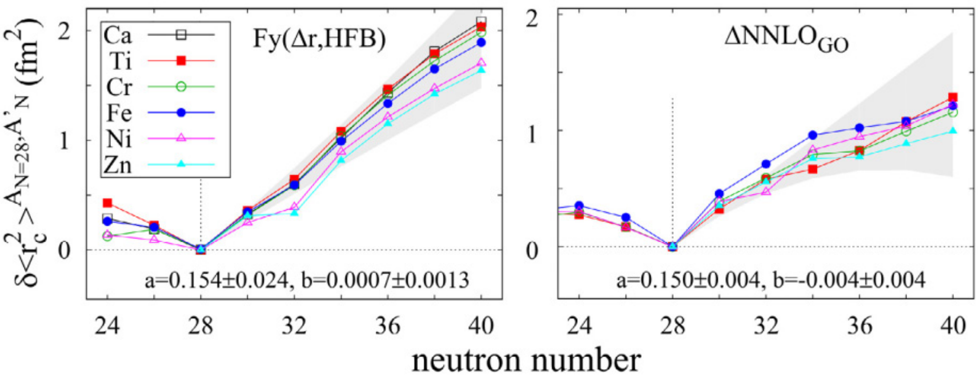
IMPACT OF NUCLEAR DEFORMATION AND PAIRING ON THE CHARGE RADII OF PALLADIUM ISOTOPES

The impact of nuclear deformation shows up in the systematics of the nuclear charge radii, with radii generally expanding with increasing deformation. In recent collaborative work between our group and the exotic nuclei and beams group, we investigated the nuclear charge radii of palladium isotopes [2]. The data measured at IGISOL allowed the testing of various nuclear DFT-based models. With the Fayans energy density functional, in addition to deformation effects, we demonstrated a clear link between the charge radii and pairing correlations. While this allows accurate reproduction of the charge radius in neutron-rich Pd isotopes, it leads at the same time to an overestimated odd-even staggering of the radius.

Selected publications

[1] M. Kortelainen, Z. Sun, G. Hagen, et al., Phys. Rev. C 105, L021303 (2022)

[2] S. Geldhof, M. Kortelainen, O. Beliuskina, et al., Phys. Rev. Lett. 128, 152501 (2022)



↑ Figure 1. Computed differential charge radii in Ca-Zn isotopes [1].

RADIATION EFFECTS

Staff Scientist Heikki Kettunen
Senior Researcher Arto Javanainen

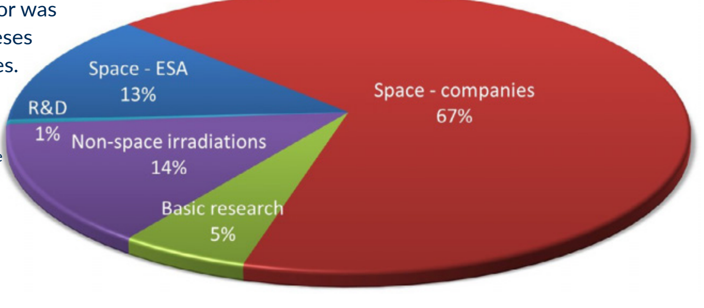
We specialize in applied research around nuclear and accelerator-based technology and operate the Radiation Effects Facility, RADEF, for the studies of radiation effects in electronics and related materials. RADEF officially became an ESA-supported European Component Irradiation Facility (ECIF) in 2005. Since then, we have carried out irradiation tests not only for ESA and the European space industry, but also for other world leading space organizations (e.g., NASA, JAXA, CNES), companies and universities. The latest contract with ESA ended at the end of 2022 and negotiation for a new 5-year contract is ongoing.

https://www.jyu.fi/en/research-groups/radiation-effects-and-industrial-applications

Four different heavy ion cocktails, proton, X-ray, and electron beams are available for irradiation tests at RADEF. The most used beam is 16.3 MeV/n heavy ion cocktail. The selection of available ions in the cocktails are developed continuously with the Ion Source group.

RADEF used 1360 hours of the K130-cyclotron beam in 63 campaigns with 33 different companies, institutes, and universities in 2022. This corresponds to 22 % of the K130 beam time hours. The distribution of this beam time between different users is shown in Fig.1. The total revenue of RADEF (commercial, EU and ESA projects) was about 1.1 M€ in 2022.

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



→ Figure 1.
Distribution of RADEF beam time hours for different activities.

ESA PROJECTS

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

In order to improve standard test methods to characterize proton SEE sensitivity in modern memory devices due to proton direct ionization, and then estimate the error 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 beams for this study, RADEF has performed simulations and numerical studies to complement the experimental results. The objective is to build models and calculation methods to estimate soft error rates in space that will take into account contributions of low and high energy protons, but also heavy ions present in radiation environments.

Radiation Characterisation of EEE components for ESA space applications

Commercial Off The Shelf (COTS) electronics have become increasingly popular for space applications in 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 an ESA-funded project with Beyond Gravity Finland Oy (formerly RUAG Space Finland) in order to perform radiation effect tests on various electronics devices that are candidates for ESA space missions.

EU PROJECT

RADNEXT

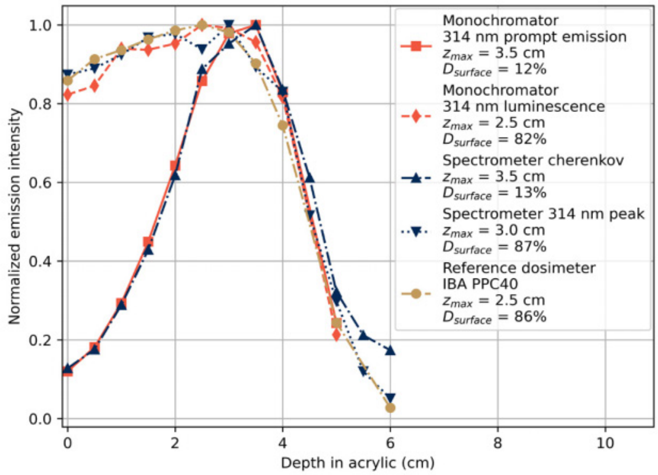
The EU Horizon-2020 project called "RADiation facility Network for the EXploration of effects for indusTry and research" (RADNEXT) was granted funding in 2020. This 4-year and 5 Meur project is coordinated by CERN with 31 participants from 12 countries. The implementation of the project started in the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

RESEARCH

Dose-depth measurements of electron-beams with optical fibre dosimeters

Dosimetry systems based on optical fibres have been tested at RADEF in collaboration with the Université Jean-Monnet in Saint-Etienne, France, using the Clinac at RADEF. The dosimeters are based on the radioluminescence of doped silica glass rods. Among the tested dopants were Gd^{3+}-ions, that have a narrow emission line around 314 nm. The tested silica glass rods have a small volume, with a length of 1 cm and a diameter of 1 mm, and they are inert and stable which allows use in various applications, such as in radiotherapy. The emissions in the visible to UV domain can be mixed with or overshadowed by Cherenkov radiation, which might need to be separated from the radioluminescence.

In the studies done with the fibre-based dosimeters during 2022, the emissions from the tested samples were studied using the monochromator POSSU developed at JYU. The radioluminescence of Gd^{3+}-ions has a long decay time, around 1.3 ms, which, when a pulsed radiation source is used, makes it possible to separate temporally from the prompt Cherenkov radiation emissions. An optical spectrometer was also used to analyse the emissions from the samples, which allowed separating the luminescence peak from the Cherenkov background based on the emission spectrum. The figure shows the light emissions of the Gd^{3+}-doped silica as a function of depth in acrylic, compared to the measured dose-depth curve. The separated luminescence at 314 nm follows the dose-depth curve, while the prompt Cherenkov radiation has a different depth profile.



↑ Figure 2. Radiation-induced emissions in the fibre-based dosimeter as a function of depth in acrylic, separated into radiation-induced luminescence of the dopant Gd^{3+} and the induced Cherenkov radiation. Data from experiments using both the monochromator POSSU and an optical spectrometer.

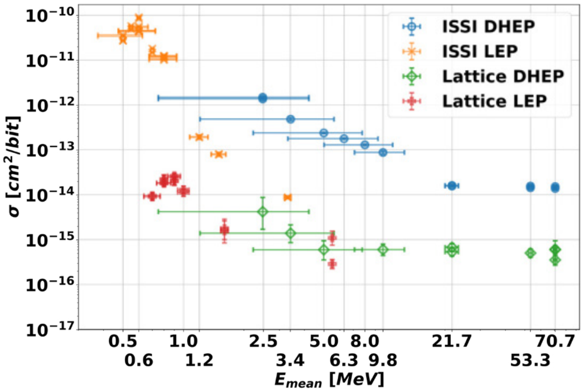
Selected publications:

D. Söderström, O. Timonen, H. Kettunen, A. Javanainen et al., "Properties of Gd-doped Sol-gel Silica Glass Radioluminescence under Electron Beams", Sensors 2022, 22(23), 9248, *http://doi.org/10.3390/s22239248*.

Low Energy Proton Testing and Modeling

Typically, single event effects (SEE) are attributed to heavy ions and high energy protons, while low energy protons (below ~3MeV) have not been considered to be an issue. However, modern, highly scaled technologies have been shown to be potentially sensitive to SEE from low energy protons (LEP). This has implications not only for satellite applications, but also at ground level as the ionization from low energy muons is very similar to that of low energy protons.

To assess the low energy proton sensitivity of a device, LEP testing is required. As a part of this project, two different low energy proton test methods were compared, and their advantages and disadvantages were examined. One method uses quasi-monoenergetic (QME) LEP beams with well-defined energies, which only contain a narrow range of proton energies. Contrarily, the other method uses heavily degraded high energy proton (DHEP) beams, which results in a very wide range of proton energies, including low energies. Overall, the two methods provided similar results in regard to the estimated error rates in the assumed operation environments. However, the DHEP method requires more efforts on the beam characterization and in the data postprocessing. Furthermore, the error rate calculations are bound to only a single approach when using data from this method. The QME LEP method requires the devices under test to be prepared by reducing the overlayers which enables the LEP beams to reach the sensitive area of the device. Otherwise, this method requires no extra beam characterization or additional data postprocessing in addition to the normal procedures usually required in SEE testing. Finally, models have been developed to extract rectangular parallelepiped (RPP) geometry parameters from SEU cross-section data obtained from both the QME LEP and DHEP tests.



↑ Figure 3. The measured SEE cross-section σ in cm2/bit as a function of the mean proton energy *Emean* in MeV. The results for two devices (ISSI, Lattice) are shown from the LEP and the DHEP test methods. The horizontal error bars indicate the full width at half maximum of the beam spectra.

Selected publications:

S. Lüdeke, G. Durán Cardenás, W. Hajdas, J. Jaatinen, H. Kettunen, C. Poivey, M. Rossi, B. Tanios, S. Vogiatzi, A. Javanainen, "Proton Direct Ionization in Sub-Micron Technologies: Test Methodologies and Modelling", in IEEE Transactions on Nuclear Science accepted for publication, doi: 10.1109/TNS.2023.3255008

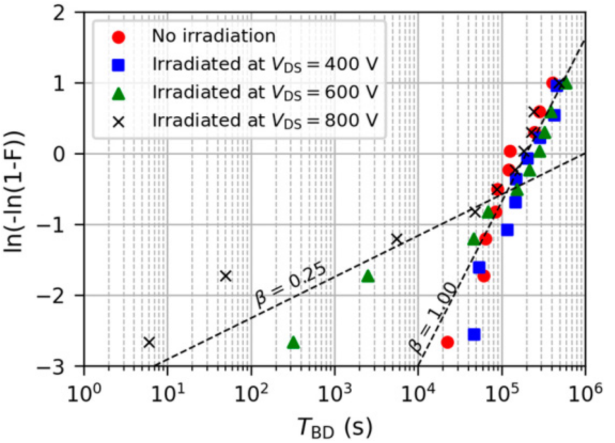
S. Lüdeke and A. Javanainen, "Proton Direct Ionization in Sub-Micron Technologies: Numerical Method for RPP Parameter Extraction," in IEEE Transactions on Nuclear Science, vol. 69, no. 3, pp. 254-263, March 2022, doi: 10.1109/TNS.2022.3147592

Radiation effects on silicon carbide-based power electronics devices

Silicon carbide (SiC) has recently gained interest in power electronics applications due to its superior material properties over silicon. SiC is a wide bandgap material that has a high critical electric field, high thermal conductivity and a high melting point which are favourable properties when high power density is needed. However, it has been found that SiC power devices are sensitive to permanent (destructive and non-destructive) single event effects (SEE) due to radiation impact in space and atmospheric environments. The generated charge by an energetic particle hitting an electronics device can hinder the device functionality and in the worst case, cause permanent damage in the device.

The charge deposition by the direct ionization from a proton impact is not likely to cause observable effects in such devices. However, the secondary particles from the interaction of the primary proton beam with the target material may generate enough charge in order to cause destructive SEE, such as single event burnout (SEB). SEB is known to be dependent on the applied voltage across the device. Moreover, the radiation exposure can induce latent damage in the device structure that may not manifest itself as an immediate failure but as a reduction of the long-term reliability.

The effects of proton [1] and electron [2] radiation on the reliability of SiC power MOSFETs have been studied at RADEF. Irradiated components were exposed to accelerated voltage stress at the gate terminal of MOSFETs in order to analyse the impact of radiation on the device lifetime. It was observed that on top of the SEB sensitivity, the lifetime degradation is also voltage dependent, which was indicated by early failures in the accelerated stress test (Fig. 1). That indicates that the oxide degradation process is driven by the synergistic effect of ionization in the gate oxide and the charge transport in the epitaxial layer of voltage biased SiC MOSFET.



↑ Figure 4. The time-to-breakdown distributions of gate oxide for fresh and irradiated devices. The extrinsic tail of early failures can be seen for devices irradiated at V_{DS} =600 V and 800 V. The dashed lines are given as a guide to the eye to emphasize the two different breakdown mechanisms. In general, β < 1indicates early failures.

Selected publications:

[1] K. Niskanen et al., "Proton irradiation-induced reliability degradation of SiC power MOSFET," IEEE Transactions on Nuclear Science, 2023

[2] K. Niskanen et al., "Effect of 20 MeV Electron Radiation on Long Term Reliability of SiC Power MOSFETs," IEEE Transactions on Nuclear Science, 2023

ION SOURCES

Senior Lecturer Hannu Koivisto
Staff Scientist Ville Toivanen

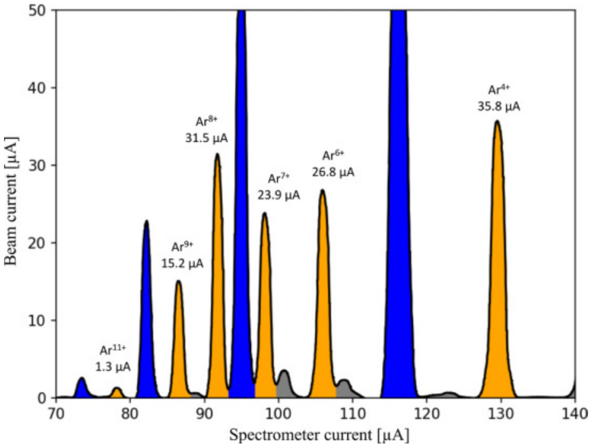
The ion source group develops ion sources and ion beams for the users of the JYFL Accelerator Laboratory. The group also conducts plasma research and development of plasma and ion beam diagnostics. The main objective of the group is to improve highly charged ion beams for the international user community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

https://www.jyu.fi/en/research-groups/ion-source-group

STATUS OF THE CUBE PROTOTYPE

The Academy of Finland granted a four-year funding (1.9.2018–31.8.2022) for the project: *"The effect of a magnetic field configuration on the performance of an ECR ion sources"*. As a part of this project an innovative ECR ion source, called CUBE, has been designed and constructed. The construction was mainly realized during 2020 and the first ion beams were successfully extracted in 2021. Experimental campaigns were carried out during 2022 to define the main properties and specifications of the CUBE ion source. The bremsstrahlung experiments confirmed that the electron heating process and the electron energy distribution of CUBE resemble those of a conventional minimum-B ECRIS [1]. In addition, the pulsed operation mode revealed an afterglow peak indicating that highly charged ions are electrostatically confined in a similar way as in a conventional ECRIS. These results together proved that CUBE has efficient plasma heating and adequate plasma confinement properties to produce highly charged ion beams.

The CUBE beam properties were systematically studied first with a round 8 mm extraction aperture using the extraction voltage of 10 kV. This allowed a direct comparison with a conventional ECR ion source. The beam properties were further studied using 4x20 mm and 4x40 mm slit extraction apertures to optimize the beam formation and beam transfer from the quadrupole-like magnetic field topology of CUBE. Figure 1 shows the charge state distribution of argon ion beams through the 4x40 mm slit extraction. The figure reveals that the performance of CUBE clearly exceeds the original target set for the project (1 µA for Ar^{10+}). As another part of the Academy project Bichu Bhaskar completed his PhD work and successfully defended his thesis, titled "Experimental study on kinetic instabilities in Electron Cyclotron Resonance heated plasma", in May 2022. We can summarize that as a result of the Academy project, we have made significant advances in ion source technology and gained valuable new information concerning the properties of ECR plasma instabilities and how they influence the highly charged ion production (12 class A1 articles).



↑ Figure 1. Charge state distribution of ^{40}Ar ion beam produced with the CUBE ion source. The ion source was tuned for Ar^{9+} ion beam at 10 kV extraction voltage using plasma heating power of 250 W and slit extraction. Oxygen was used as a mixing gas.

ERIBS: EUROPEAN COLLABORATION ON ECR ION SOURCES

ERIBS (European Research Infrastructure – Beam Services) brings together *participant research teams* from nine different laboratories developing ECR ion sources and their beams. The project is coordinated by H. Koivisto (JYFL) and it is a part of the large *EURO-LABS* consortium funded by the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511 for the period 1.9.2022-31.8.2026. EURO-LABS brings together for the first time in Europe the three communities engaged in Nuclear Physics and Accelerator/ Detector technology for High Energy Physics.

The ERIBS project aims at providing high-level ion beam services for the EURO-LABS research infrastructures by focusing on improvements in two key categories:

- **Task 1: Ion beam variety and production efficiency**. This task aims to improve the production of metal ion beams for the EURO-LABS user community.
- **Task 2: Short and long-term ion beam stability**. This task aims to improve the operation stability and durability of highly charged ion beams.

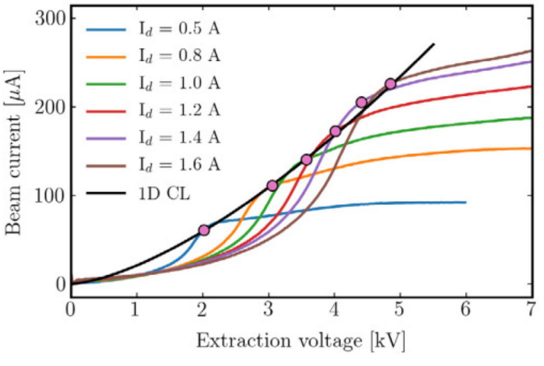
The ERIBS kick-off meeting was organized by the GSI ion source team at GSI 25-26th September 2022. During the meeting, the detailed planning for the schedule, the distribution of human resources and knowledge transfer was completed. More information related to the ERIBS project can be found via the dedicated website: *https://wiki.jyu.fi/x/hI4iBg*

RESEARCH AND DEVELOPMENT FOR ION SOURCES AND THEIR PLASMAS

The high-resolution visible light spectrometer POSSU, developed at JYFL Acclab, was upgraded during 2022. The main objective of the upgrade was to make time-resolved light emission measurements of highly charged plasma at the millisecond time scale possible without compromising its world-class spectral resolution (10 pm). The upgraded version will allow for the first time, for example, to measure temperature dependence of ions during different plasma transients. Systematic time-dependent plasma studies, which together with the realization of the POSSU upgrade forms the main part of the PhD work of O. Timonen, will be started during 2023.

The understanding of plasma ion source beam extraction systems has traditionally been based on the assumption of space charge limited operation. This assumption has now been re-evaluated by S. Kosonen as part of his PhD work in a study that combines a comprehensive set of experiments and simulations to probe the plasma ion source beam formation process. The results show that in fact under these conditions the beam extraction is governed by limitations arising from initial beam divergence and geometric restrictions, not space charge effects described by the well-known Child-Langmuir law, which only emerges with fixed divergence conditions (Fig. 2). This new insight is expected to lead to a paradigm shift in the framework that is used to understand – and design – plasma ion source beam extraction systems in the future [2].

The research and development work were continued to further develop the non-invasive consecutive transients (CT) method developed during the PhD work of M. Luntinen. The method is used to obtain estimates for the properties of ECR-heated plasmas (e.g. electron density and characteristic times) by injecting short pulses of 1+ ions into a highly charged main plasma and by measuring the transients of charge bred highly charged ion beam pulses after the ion source. Improving the accuracy of the method was successfully studied by using short pulses of multicomponent 1+ injection, which revealed that the multicomponent injection reduced the uncertainty of the method especially for the estimates of plasma density and average electron energy. In addition, the impact of the assumed electron energy distribution function and uncertainty of other input parameters on the accuracy of the method were investigated. See Ref. [3] for further details.



↑ Figure 2. Extracted beam current of Ar^+ as a function of extraction voltage with different plasma densities (described by the discharge current I_d). The behavior of the extracted currents (solid lines) is determined by beam divergence related limitations. The Child-Langmuir space charge limit emerges only at points of constant divergence (circles).

Selected publications:

[1] T. Kalvas, V. Toivanen, S. T. Kosonen, H. Koivisto, O. Tarvainen and L. Maunoury, First results of a new quadrupole minimum-B permanent magnet electron cyclotron resonance ion source, Plasma Sources Sci. Technol. 31 (2022) 12LT02.

[2] S.T. Kosonen, T. Kalvas, V. Toivanen, O. Tarvainen, and D. Faircloth, Critical assessment of the applicability of the Child-Langmuir law to plasma ion source extraction systems, submitted to Plasma Sources Sci. Technol. (2023).

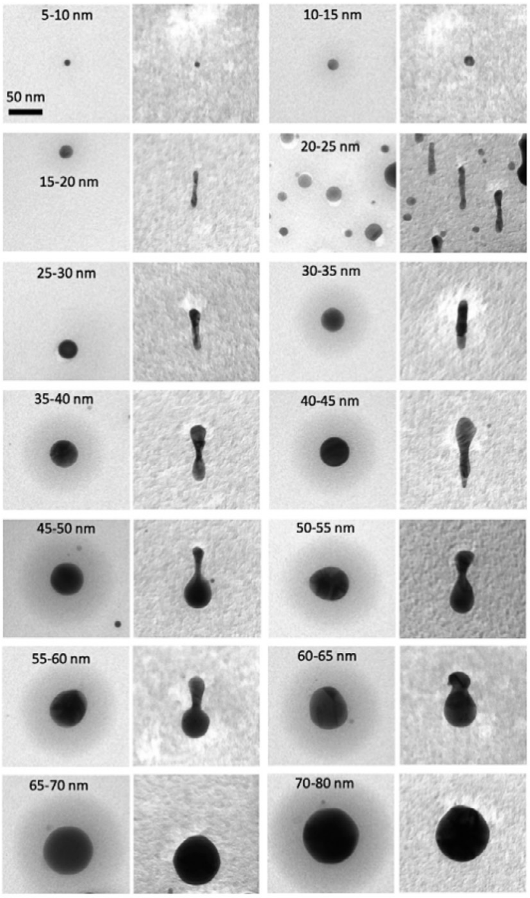
[3] M. Luntinen, V. Toivanen, H. Koivisto, J. Angot, T. Thuillier, O. Tarvainen, and G. Castro, Diagnostics of highly charged plasmas with multicomponent 1+ ion injection, Phys. Rev. E 106, Nov. (2022), p. 055208.

ACCELERATOR BASED MATERIALS PHYSICS

Professor Timo Sajavaara,
Academy Research Fellow Mikko Laitinen

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

The PhD thesis work of Spyridon Korkos culminated in a dissertation on Ion beam shaping of embedded metallic nanoparticles for photonic applications. The results showed that the ion beam irradiated nanoparticle elongation depends strongly on the deposition process of SiO2 and the SiO2 quality, in addition to the initial size of the nanoparticles embedded in the oxide layer. Consequently, ALD SiO2 offers greater elongation than PECVD SiO2. In addition, the irradiation of spherical nanoparticles embedded in other materials, such as Al2O3 and TiO2, was done. While TiO2 deposited by ALD offers significantly smaller elongation for the gold nanoparticles compared to SiO2, nanoparticles embedded in Al2O3 deposited by ALD elongated similarly as in ALD SiO2. In this study, a new methodology was applied by using a thin Si3N4 TEM windows grid as a substrate in order to be able to trace the same nanoparticle before and after the irradiation.



↑ Figure 1. TEM images of nanoparticles sandwiched between two 50 nm ALD SiO2 layers (annealed after the deposition). The samples were irradiated with ^{127}I at a fluence of 5×10^{14} ions/cm^2 before (left) and after (right) the irradiation. From [1].

COMBINATION OF INDUSTRIAL COLLABORATION AND RESEARCH

One major milestone was reached as the ToF-ERD spectrometer was delivered to the University of Surrey. This was a major effort from the research group and help also from the other Accelerator Laboratory staff was highly appreciated. The commercial turnover of more than 0.5 M€ also enabled us to hire a new doctorial researcher for the research group. This new PhD work related to the sputtering ion sources known as SNICS lead to a patent application during 2022, where one major motivation and discovery is thought to be the instantaneous Cs-coverage control by the developed laser system. This topic also received 2 best poster awards received by doctoral researcher Akbar Hossain in the ECAART and NIBS conferences.

ION-BEAM ANALYSIS

The Academy Research Fellow project lead by Mikko Laitinen continued to measure and identify the mismatch of heavy low energy ions in the ToF-ERD telescope and the theoretically predicted yield. The yields seem to indicate that for lowest energy heavy ions (Au, < 10 MeV) the detected yields at the telescope count only about 30% of the expected yields, even after the Andersen Screening correction. The earlier thought rule of the thumb, however, seems to hold after the newest data and scattering a light beam from heavy target elements can still be used as valid. For the same project, doctoral researcher Mikko Kivekäs spent 3 months at ETH Zurich during the summer 2022. There he measured different heavy gases in the Gas ionization detector, measuring their speed (and energy) resolutions for different ion species and fluxes. Here the first conclusions seem to indicate that it could be possible to use even thinner SiN entrance windows at the gas detectors. This could be realized by using heavier hydrocarbons having equal stopping and energy resolutions than the currently widely used isobutane.

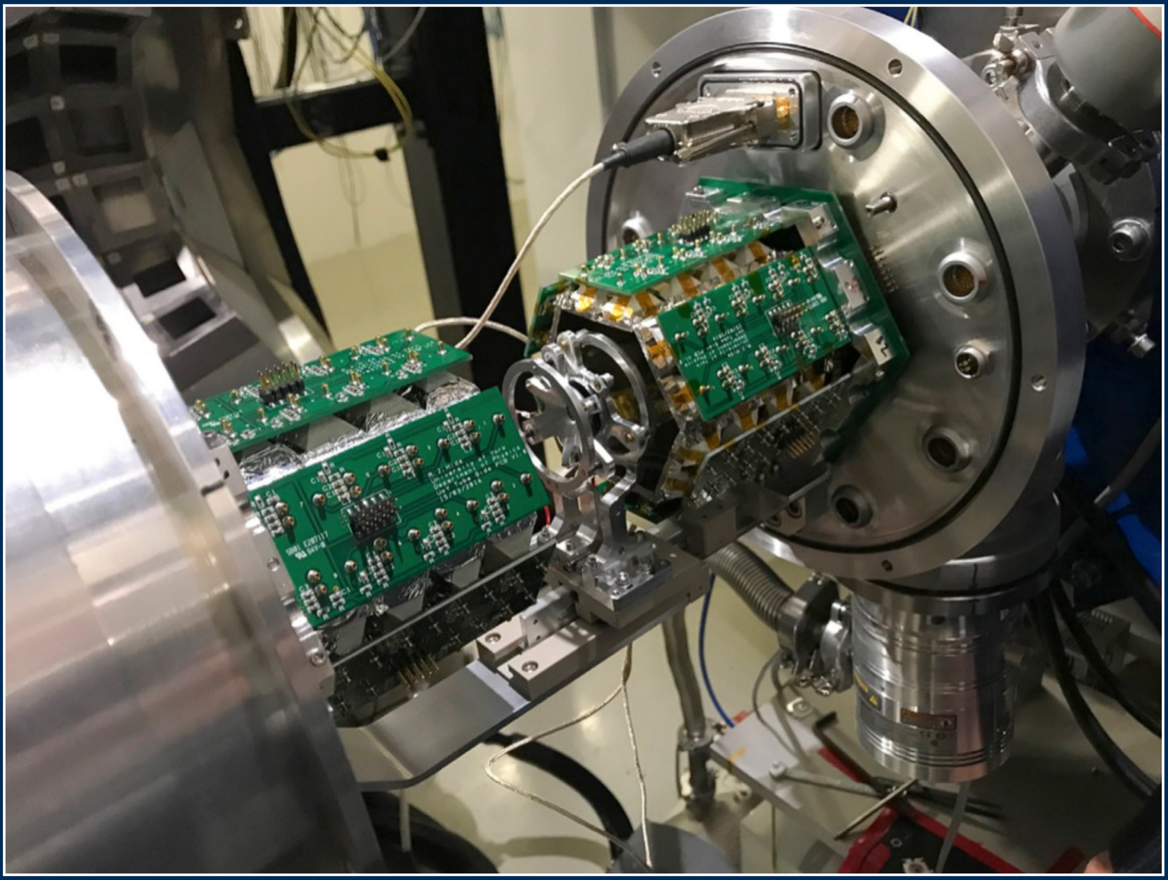
The ToF-ERD analysis program Potku also continued to develop during 2022. A new release was pushed out in the spring, but the most exhaustive development started after that. The newly modified back-end code was changed heavily to accommodate for example new Python versions, new configuration files by JSON, source code auto-compile and version numbering scheme options by GitHub, a faster interface for spectra and cut files, which can now also be modified and copied to the 2023-released version, and also important user features and ease-of-use options for the MCERD simulation side.

Selected publications:

[1] S. Korkos, K. Mizohata, S. Kinnunen, T. Sajavaara and K. Arstila (2022). Size dependent swift heavy ion induced Au nanoparticle elongation in SiO2 matrix. *Journal of Applied Physics*, 132(4), Article 045901. https://doi.org/10.1063/5.0099164

[2] S. Kinnunen, and T. Sajavaara (2022). Spatial ALD of Al2O3 and ZnO using heavy water. *Surface and Coatings Technology*, *441*, Article 128456. https://doi.org/10.1016/j.surfcoat.2022.128456

[3] A. Hossain, O. Tarvainen, M. Reponen, R. Kronholm, J. Julin, T. Kalvas, V. Toivanen, M. Kivekäs and M. Laitinen (2022). Photo-enhanced O−, H− and Br− ion production in caesium sputter negative ion source : no evidence for resonant ion pair production. *Journal of Physics D: Applied Physics*, *55*(44), Article 445202. https://doi.org/10.1088/1361-6463/ac8e79



CENTER OF EXCELLENCE IN QUARK MATTER

Professor Tuomas Lappi
CoE director

The year 2022 was the first operational year of the new Academy of Finland Center of Excellence in Quark Matter. The Center unites the traditionally strongly interacting QCD theory and ALICE experimental groups at Jyväskylä under one umbrella, creating a community of about 40 researchers. The CoE period will run for 8 years, until the end of 2029, subject to a successful midterm evaluation.

The start of the CoE naturally brought with it a new source of funding, and consequently a new set of people, students, postdocs and more senior researchers. On the experimental side schedules are more flexible, and new people started joining along the spring. Theorists tend to exhibit more of a collective motion, with migratory patterns peaking in the fall. Thus, it took until October before the CoE reached its current size. In November the CoE personnel spent two days at a retreat at the Konnevesi research station. The primary purpose of this retreat was to get the group members to know each other and provide an overview of the kinds of research that other CoE members are working on. We of course also warmed up the sauna and went on a walk to get familiar with Finnish nature. From my point of view, and also according to the collected feedback, the retreat was a very successful event, and really crystallized some of the best aspects of the kind of research community that we can be.

Only a few weeks later we had the first meeting of the Scientific Advisory Board (SAB) of the CoE. The expert members prof Olga Evdokimov and prof. Mike Strickland, together with prof. Pekka Pankka and Samuli Hemming representing the Academy, visited us for two intense days of discussions on both physics and future plans in terms of funding, personnel etc. The SAB meeting further reinforced my feeling that we are on the right track, both scientifically and as a community. The report written after the visit was very positive overall, but of course came with many suggestions for further improvements which are very valuable for us. At least I ended the first year of the CoE on a very positive feeling.

↑ Personnel of the CoE at the Konnevesi research station, November 2022

QCD THEORY

Professors Kari J. Eskola and Tuomas Lappi
Senior Lecturer Hannu Paukkunen
Academy Research Fellows
Heikki Mäntysaari and Ilkka Helenius
University Researcher Harri Niemi

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.

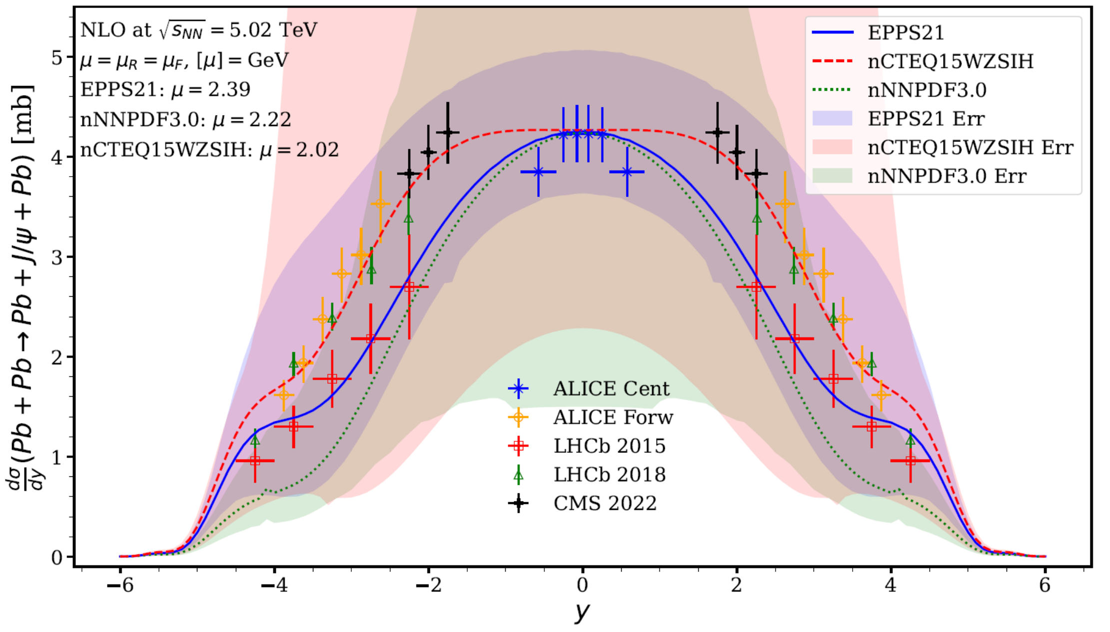
https://www.jyu.fi/en/research-groups/qcd-theory

The first year of the CoE marked the arrival of several new members in the group. Jussi Auvinen and Vadim Guzey returned to Jyväskylä as University Researchers and Anh-Dung Le, Josh Tawabutr, Yuuka Kanakubo, Pit Duwentäster and Jarkko Peuron started as postdocs. Dana Avramescu and Joni Laulainen started as new graduate students. Chris Flett moved to a new postdoc position at Orsay, Florian Cougoulic to start the second half of his joint STRONG-2020 postdoc position at Santiago de Compostela and Henri Hänninen to the Department of Mathematics.

PERTURBATIVE QCD: EXCLUSIVE VECTOR MESONS AND PYTHIA DEVELOPMENT

The exclusive production of heavy vector mesons – bound states of a heavy quark and its antiquark – in high-energy nucleus-nucleus collisions is a topic that is subject to active theoretical and experimental research. In these ultraperipheral processes the approaching nuclei do not actually collide and thereby break up, but the interaction happens at a distance, the electromagnetic field of one of the nuclei probing the inner structure of the other nucleus. A persistent belief in the field – dating back to early 90's – has been that this process is extremely sensitive to the gluon content of the nucleus, encoded into nuclear parton distribution functions (PDFs). We have studied this statement through a rigorous next-to-leading order perturbative QCD calculation in Pb-Pb collisions [1] and compared our results with the LHC data on J/Psi (bound state of a charm quark and its antiquark) production. While the world data agrees with our calculations (see Fig.1) we found that the production cross sections carry a significant sensitivity also to the quark content of the nucleus. As a result, the interpretation of the measurements at the LHC turns out not to be as straightforward as has been thought.

Another significant effort is the development and support of PYTHIA Monte Carlo event generator aiming to simulate high-energy collisions in various experimental configurations. This is an international collaboration with members from US, Europe, India and Australia and a significant contribution from Jyväskylä. In Jyväskylä the key areas involve further development in modelling collisions involving an intermediate photon and/or a nuclear target. The local team members are in key positions in the collaboration: I. Helenius acting currently as a deputy spokesperson and M. Utheim as a deputy codemaster. As a highlight, a new version of the complete physics manual for the latest 8.3 series was published 2022 with significant contributions from the pQCD team members [2]. This supersedes the previous highly cited physics manual written for Pythia 6.4 more than fifteen years ago.



↑ Figure 1. The available LHC data on exclusive J/Psi production in Pb+Pb collisions at 5.02 TeV center-of-mass energy compared with next-to-leading order predictions with different contemporary nuclear PDFs and their uncertainties. Figure based on Ref. [1].

HYDRODYNAMIC SIMULATIONS

Fluid dynamics is a central tool in understanding the dynamics and properties of strongly interacting QCD-matter formed in ultrarelativistic heavy-ion collisions at LHC and RHIC.

In 2022, developing the theory of relativistic fluid dynamics further, we generalized the formalism of relativistic second-order transient fluid dynamics to multicomponent systems by deriving the relevant equations of motion from the relativistic Boltzmann equation [3]. This is particularly important in modeling QCD fluids that can consist of hundreds of different types of strongly interacting particles. In describing the fluid dynamical evolution of heavy-ion collisions, we extended our framework, whose initial conditions are computed from the EKRT saturation model, to account for the bulk viscosity and system-size dependent decoupling dynamics of the fluid to free particles [4]. This extended the excellent global agreement of the model with LHC and RHIC data towards peripheral nuclear collisions that typically pose a challenge for fluid dynamical models. In 2022, aiming at significantly speeding up the extensive hydrodynamic simulations necessary for collecting sufficient statistics for rare correlators, we were also building a neural network that can predict the results of hydrodynamic simulations from the initial conditions alone. We are also building a Monte-Carlo EKRT event-generator that includes new sources of fluctuations in the initial particle production that are important in small collision systems and at off-central rapidities.

NON-LINEAR QCD AT HIGH ENERGIES

Exclusive vector meson production that is discussed above is also a central process when probing non-linear QCD phenomena with extremely dense nuclear targets in ultraperipheral collisions and at the future Electron-Ion Collider. In 2022 we completed the calculation of heavy vector meson production at next-to-leading order accuracy in the Color Glass Condensate framework including non-linear QCD effects. In addition to heavy mesons, we calculated the cross section for exclusive production of light vector mesons in the limit where the high virtuality of the photon allows for perturbative calculations.

These developments became possible thanks to the foundational work that we also completed in 2022: we finalized the calculation of the virtual photon wave function describing the photon splitting to the quark-antiquark pair at next-to-leading order accuracy in light cone perturbation theory including the quark mass. Our numerical analysis showed that these higher-order corrections are necessary in order to simultaneously describe all high-energy proton structure function data from the electron-proton collisions measured at HERA [5]. We also initiated the calculation of diffractive cross sections in deep inelastic scattering at next-to-leading order accuracy, publishing the contribution from the quark-antiquark-gluon production that dominates in the limit of high photon virtuality.

In addition to developing the theoretical framework to next-to-leading order accuracy, we also performed extensive phenomenological analyses at leading order in the Color Glass Condensate framework. We continued our work to probe the proton fluctuating substructure by determining analytically how different vector meson production cross sections constrain these fluctuations, and by using a Bayesian inference approach to determine the parameters describing the geometry fluctuations, among their uncertainties, from the HERA data. By comparing the proton structure functions calculated from the Color Glass Condensate framework to the linear collinear factorization-based approach we quantified the magnitude of saturation effects that are expected to be seen at the Electron-Ion Collier [6]. In studies related to the spin-structure of the proton, we developed a new evolution equation describing how the gluons carrying a small fraction of the proton momentum contribute to the total proton spin 1/2.

Selected publications

[1] K.J. Eskola, C.A. Flett, V. Guzey, T. Löytäinen and H. Paukkunen, Phys. Rev. C 106 (2022) 3, 035202

[2] C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius *et al.*, SciPost Phys. Codebases 8 (2022)

[3] J. A. Fotakis, E. Molnar, H. Niemi, C. Greiner and D. H. Rischke, Phys. Rev. D 106, no.3, 036009 (2022)

[4] H. Hirvonen, K. J. Eskola and H. Niemi, Phys. Rev. C 106, no.4, 044913 (2022)

[5] H. Hänninen, H. Mäntysaari, R. Paatelainen, J. Penttala, arXiv:2211.03504 [hep-ph]

[6] N. Armesto, T. Lappi, H. Mäntysaari, H. Paukkunen, M. Tevio, Phys. Rev. D 105 (2022) no. 11, 114017

ALICE EXPERIMENT AT THE CERN LHC

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

ALICE (A Large Ion Collider Experiment) at the CERN LHC (Large Hadron Collider) is dedicated to the study of the properties of quark-gluon plasma (QGP). QGP is a state of matter where partons are no longer confined inside the hadrons. ALICE can track and identify particles down to low transverse momenta, allowing detailed studies of the essential properties of the QGP.

The ALICE physics program includes proton, lead, and oxygen collisions. In 2019–2021 ALICE underwent a significant upgrade, and 2022 was the first running year of ALICE 2 – a thoroughly modernised experiment with three new detectors, including FIT – The Fast Interaction Trigger.

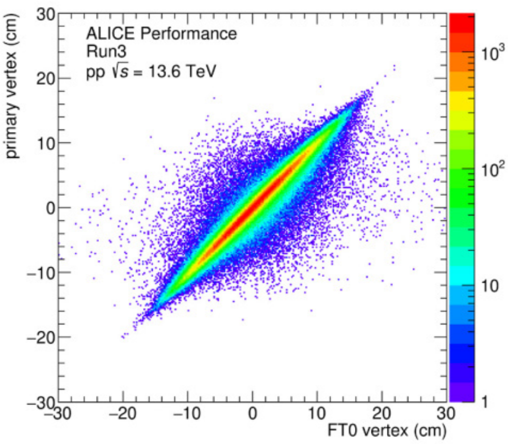
The ALICE collaboration has ~2 000 members from 171 institutes in 40 countries. JYFL and HIP have been ALICE members since November 1997. ALICE activities in Jyväskylä are part of the Centre of Excellence (CoE) in Quark Matter at the Finnish Academy.

https://www.jyu.fi/en/research-groups/the-alice-experiment

The year 2022 was the first year of operation of ALICE 2 – a thoroughly modernized experiment capable of detecting, processing, and recording high-luminosity collisions delivered by the upgraded LHC. The new ITS (Inner Tracking System) and MFT (Muon Forward Tracker) significantly improved ALICE 2 tracking, and the new FIT (Fast Interaction Trigger) monitors collision properties and measures the interaction time with picosecond precision. The biggest challenge was data handling from the TPC (Time Projection Chamber) - the largest and slowest ALICE detector. With forty million LHC collisions per second, we had to change to a continuous readout of the TPC and process 3.5 TB of data per second! That required new electronics, a modern computer farm and O^2 – a sophisticated online-offline analysis framework. Our group contributed to the quality assurance of the GEM foils used in the new TPC readout. In 2022, ALICE measured ~10^{12} minimum bias (MB) pp-events, which is about 300 times the combined statistics collected in the first two LHC running periods.

↓ Figure 1. ALICE people celebrating the successful heavy ion pilot run in 2022.

Our group has been responsible for FIT since 2013 when we proposed the new detector to the ALICE collaboration. In 2022, our members served as the FIT project leader, system run coordinator, and software coordinator. FIT is essential for ALICE 2 operation. It gives inputs for the Central Trigger Processor, monitors luminosity and backgrounds, determines online vertices and collision times, and provides an unbiased sample of the forward multiplicity needed to extract the centrality and the reaction plane required in the analysis of heavy-ion collisions. It also selects ultra-peripheral events. Figure 2 is an example of the FIT performance during a 2022 pp run. It shows an excellent correlation between the online vertex position from FIT versus the vertex position extracted offline from ALICE tracking detectors.

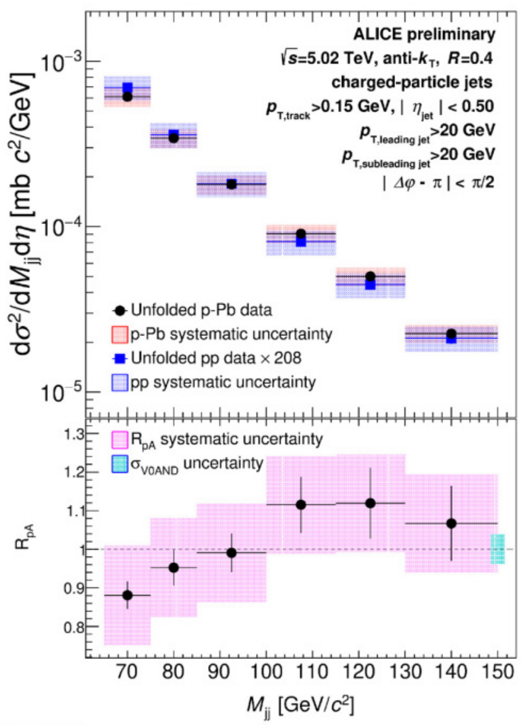


↑ Figure 2. Correlation between online vertex position, measured by FIT, and offline vertex from ALICE global tracking.

The Centre of Excellence in Quark Matter is a joint effort with the Jyväskylä theory groups addressing ALICE physics with theoretical models and testing them against measured results. Our data analysis group concentrates on collective flow and jets. We are also contributing to R&D on FoCal (Forward Calorimeter). The new detector is scheduled to complement the ALICE physics program after 2028.

Fluctuations inside the incoming nuclei cause hot spots in temperature and density distributions in the droplet of QGP created in Pb-Pb collisions at the LHC. These spatial anisotropies are converted to the detected momentum distribution anisotropies by QGP fluid pressure. We analyse the azimuthal particle distributions using Fourier expansion. The extracted Fourier coefficients are related to the transport properties of the QGP. Using this method, in 2022, we provided stringent new constraints to the shear and bulk viscosities of the QGP.

Very energetic partons, created in the primary interactions among incoming nuclei, are not expected to thermalise into the QGP. Instead, they will traverse the fireball losing their energy via gluon bremsstrahlung, leading to jet quenching. We study the jet-medium transport coefficient by measuring medium modifications in dijet mass distributions. Figure 3 presents a significant milestone in this analysis with input from both pp and p-Pb collisions. The measurement in these small systems provides a reference to the Pb-Pb analysis and constrains cold nuclear matter effects in this observable.



↑ Figure 3. Dijet mass distributions in pp and p-Pb collisions with ALICE.

Although the LHC Run 3 has only started, ALICE is preparing the subsequent upgrades. The FoCal calorimeter is one of them. FoCal will be placed outside the main ALICE magnet at small scattering angles, 7 m from the interaction point. The physics program of FoCal includes measurements constraining nuclear parton distributions at small momentum fractions and searches for direct experimental evidence for a “saturated” gluon system where gluon splitting and fusion processes are balanced. The first FoCal prototypes were already tested with PS and SPS beams. We analysed a part of the test beam results and supplemented them with extended Monte Carlo simulations.

COSMOLOGY

Professor Kimmo Kainulainen
Senior Lecturer Sami Nurmi

We study fundamental open questions in the standard cosmological LCDM-model, including the nature of Dark Matter, the origin of the baryon asymmetry and the origin of the observed large scale structures during inflation and their subsequent evolution. We also develop formal tools for treating quantum fields in out-of-equilibrium conditions and use them to study the mixing and oscillating neutrinos, particle production during and after the inflation and the leptogenesis and the electroweak baryogenesis problems.

DARK MATTER

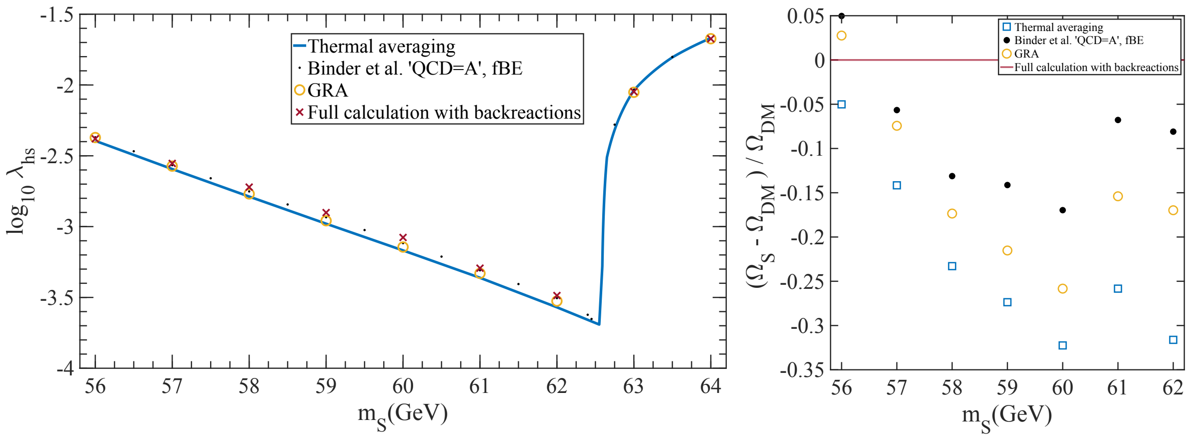
About 26% of the total energy of the universe consists of a pressureless fluid, whose precise nature remains unknown. We have studied various candidates for this dark matter (DM), ranging from different particle DM candidates to Primordial Black Holes (PBHs). We were among the first to thoroughly investigate the idea of a dark sector connected to SM via a scalar portal [1] and we showed that primordial physics at very high energies can be connected to DM and its properties, testable by precision data on cosmic structures. We also showed that inflation and reheating can rather generically influence the DM abundance in setups with a vanishingly small coupling to the SM, e.g. in [2,3]. We recently computed the DM abundance for the first time from a full momentum dependent Boltzmann equation [4], bringing the DM abundance calculations to a new level of accuracy.

QUANTUM TRANSPORT THEORY

A long-standing research line in our group is developing an advanced quantum transport theory formalism and transport equations, and their application to derive precise, testable signals related to out-of-equilibrium processes. Our tools are widely used for example in the electro-weak baryogenesis context, where they are the only known consistent method to compute the CP-violating perturbations in the out-of-equilibrium plasma [5]. They were also used to solve the leptogenesis problem in the resonant limit in [6] and they have been used to study particle production in the reheating process after inflation [3]. We are currently writing up a series of articles where they will be used to set up the theory of light neutrino mixing from first principles.

INFLATIONARY PHYSICS

We investigate the microscopical mechanism of inflation and its connection to fundamental theories of matter and gravity. We study the theoretical foundations and novel observable signals of Higgs inflation models and explore how inflation constrains the SM and its extensions through high-energy phenomena [2,3]. We work broadly on topics connected to non-perturbative infrared dynamics of light quantum fields in the inflaton sector and beyond, applying and developing the approximative stochastic formalism and testing it against first principles calculations. We are also studying new features of primordial perturbations that will be tested by future CMB and LSS surveys, quantifying their links to the inflaton sector and other matter fields. This involves e.g. inflation in quantum diffusion dominated regimes, spectral distortion signatures, gravitational waves, and primordial black holes.



↑ Figure 1. Left: fixed relic densities explaining all dark matter, from four different calculational methods (red crosses are this work). Right: relative difference in abundances computed in different approximations, when the coupling is fixed by the full calculation (red crosses on the left) to yield the correct DM abundance. The figure is from [4].

BARYON ASYMMETRY

One of the outstanding problems in the ΛCDM-model concerns the origin of the matter-antimatter, or baryon asymmetry in the Universe (BAU). The observed BAU must be created after inflation by some microphysical processes that involve physics that goes beyond the standard model of particle physics. The leading candidates to explain BAU include the leptogenesis and the electroweak baryogenesis (EWBG) mechanisms. Both scenarios need treating interacting coherent quantum fields in CP-violating, out-of-equilibrium conditions. We are world leaders in deriving and applying quantum transport methods for calculations of the BAU in these setups [4,5] and we are currently extending these methods even further. We are also building generic numerical tools for implementing our transport equations at various different approximations in practical applications.

INHOMOGENEITIES

Perhaps the most puzzling element of the ΛCDM-model is Dark Energy. Given the intrinsic assumption of homogeneity and isotropy, the DE is needed to explain the apparent acceleration of the Universe, but due to the nonlinearity of general relativity (GR), it is not clear how precise this assumption is. Moreover, several tensions have emerged from precision analyses of the statistical properties of the large-scale structure, including the H_0-anomaly and the quasar dipole anomaly, which may be signaling the existence of large scale inhomogeneities. To study the issue quantitatively, we simulate the evolution of inhomogeneities in fully nonlinear GR setups. We will use our simulated model universes to study what effects large nonlinear structures can have on cosmological observables and to see if they can alleviate some of the observed tensions.

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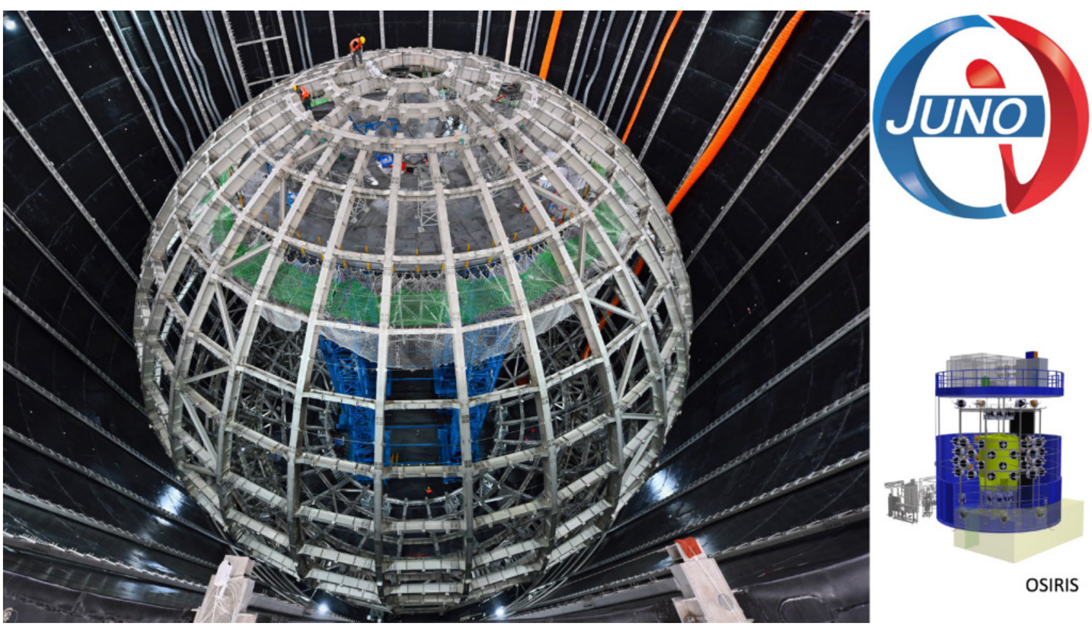
NEUTRINO AND ASTROPARTICLE PHYSICS

Senior Researcher Wladyslaw H. Trzaska

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



↑ Figure 1. JUNO & OSIRIS. Left: a June 2022 photo of the steel structure to support 35 m diameter acrylic globe holding 20 kton of LS. Right: OSISRIS sketch; the 3 m diameter, 3 m tall cylinder tank will sample each 20-ton batch of LS.

The year 2022 witnessed impressive progress at the JUNO [1] site in China's Guangdong (Canton) province. It is the only place on Earth equally distanced (52.5 km) from 8 modern, high-power nuclear reactors with a combined thermal power of nearly 30 GW and therefore the ideal spot to measure electron antineutrino oscillations. The main goal of the new 20 kton multi-purpose liquid scintillator (LS) detector is an unambiguous determination of Neutrino Mass Ordering. The formerly empty mountain valley now hosts a new campus. The underground areas, shielded by 650 m rock overburden, are reachable by a cable train moving along a 1265 m long 42% slope. The vertical shaft is also ready. The completed giant water pool is now being instrumented. A massive stainless-steel truss supports a 35-meter-diameter spherical acrylic vessel with 17612 20" photomultipliers (PMTs) and 25600 3" PMTs. The work on the central detector construction and assembly will continue throughout 2023.

Our team has been part of JUNO since the beginning of the project, conducting R&D on LS purity and even hosting meetings and workshops. Our status was formalized on January 28th, 2022, when the JyU Rector signed the Addendum to the JUNO Memorandum of Understanding. Our current activities focus on the standalone detector OSIRIS controlling JUNO's radiopurity. For the success of its science program, JUNO must reach an exceptional purity of the 20 kton LS target. Even a tiny amount of a lower-grade substance would ruin the measurements. To prevent it, before entering the main vessel, each batch of the scintillator will be tested by OSIRIS – a 20-ton mini-JUNO setup. The filing of JUNO should be completed by the end of 2024. After that, with relatively minor modifications, the OSIRIS detector can be used for neutrinoless double beta decay searches and standalone solar pp-chain neutrino precision measurements [2].

There was also significant progress at SURF in Lead, South Dakota. By the end of 2022, 400 000 tons of rock (~50%) was excavated for four large caverns to host the DUNE [3] Far Detectors. All drill-and-blast activities will be completed by the end of 2023.

At the end of November 2022, encouraged by the promising results from the NEMESIS [4] prototype, we launched NEMESIS 1.4 – a new setup located 1.4 km underground on the main level of the Pyhäsalmi mine. With only 12 muons per day per square meter, we expect to determine the source of the anomalies detected by our previous experiments. Whatever the outcome, the result will be interesting since no structures are predicted in muon-induced high-multiplicity neutron spectra. However, a hypothetical interaction of a GeV-scale WIMP with a massive lead target remains the most exciting of the possible outcomes of our measurements.

Selected publications

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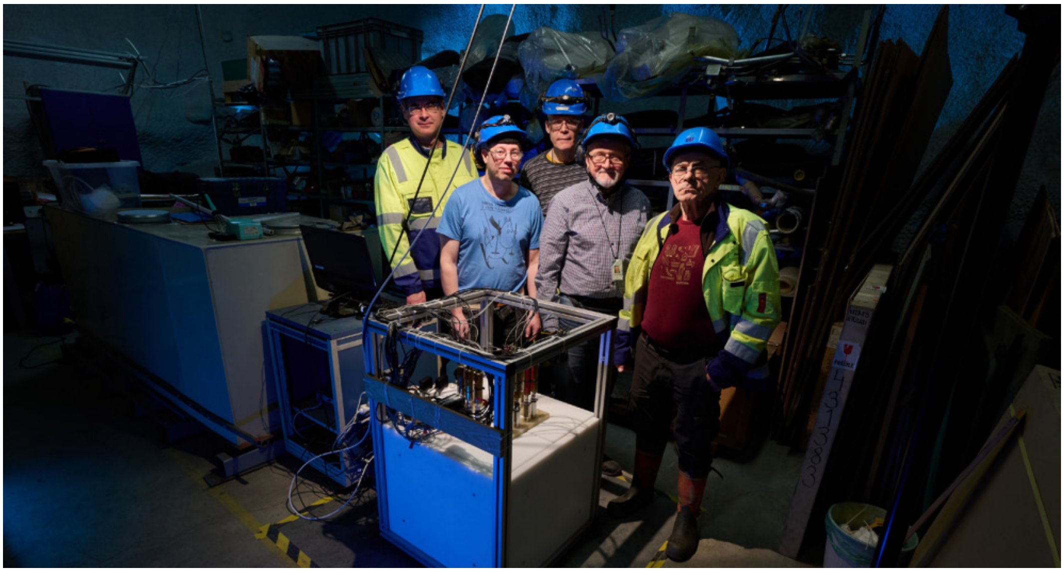


↑ Figure 2. NEMESIS 1.4 installed at a depth of 1.4 km in the Pyhäsalmi mine, November 23rd, 2022.
Standing from the left: K. Jędrzejczak, P. Kuusiniemi, T. Enqvist, W.H. Trzaska, J. Orzechowski.

INDUSTRIAL COLLABORATION

Professors Ilari Maasilta and Timo Sajavaara
Academy Research Fellow Mikko Laitinen
Senior researchers Arttu Miettinen and Arto Javanainen
Staff Scientist Heikki Kettunen

RADEF

The Radiation Effects group of the Accelerator Laboratory has continued the utilization of the RADEF facility under ESA's Technical Research Programme (TRP) since 2005. The latest contract was renewed in 2020 and continued till the end of 2022. Negotiations for a new 5-year contract are ongoing. RADEF specializes in applied research around nuclear and accelerator-based technology and operates the facility for the studies of radiation effects in electronics and related materials. We are providing K-130 cyclotron and cLinac electron accelerator beams, mainly for ESA and the European space industry for testing the radiation hardness of electronic components. The use of RADEF's commercial beam time in 2022 was 1 360 hours corresponding to 22 % of the total running hours of the K-130 cyclotron. In total, 65 test campaigns for 34 different companies were performed at RADEF. The commercial revenue was about 1.1 M€ in 2022.

RADEF is involved in several EU and ESA projects. The Erasmus Mundus Joint Master Degree programme Radiation and its Effects on MicroElectronics and Photonics Technologies (RADMEP) provides multidisciplinary and innovative MSc studies covering the interactions between Radiation and MicroElectronics and Photonics, two Key Enabling Technologies for the future of Europe. An EU Horizon-2020 project called "RADiation facility Network for the Exploration of effects for indusTry and research" (RADNEXT) started in 2021. Two ESA projects; Estimation of proton induced Single Event Effect rates in very deep submicron technologies and Radiation Characterisation of EEE components for ESA space applications were completed in 2022. In these ESA projects, RADEF acted as a subcontractor.

RADIATION PROTECTION EXPERT SERVICES

The Accelerator Laboratory has been providing expert services for companies requiring radiation protection experts (RPEs). These services are being run by the normal research staff of the department. While RPE service for companies is purely a commercial consultation service, it has been seen as an important process to constantly train our own personnel whose work includes radiation safety aspects and training of others in the Accelerator Laboratory. This both advances our own safety culture and at the same time we have 'access' to see the best practices in the industry. Annual revenue has been about 30 k€ with very small expenses, and for this reason it has been possible to buy RPE service-related equipment. These measurement equipment acquisitions support both the RPE service and also research. Acquired tools include for example the modern multi-purpose survey meter RadEye™ B20-ER, the spectroscopic personal radiation detector RadEye™ SPRD-GN, also suitable for neutrons, and the most recent hand-held XRF tool NITOL XL5 Plus.

COMMERCIAL RESEARCH EQUIPMENT DELIVERIES

The Accelerator Based Materials Research group delivered in 2022 the first full ToF-ERDA (Time-of-Flight Elastic Recoil Detection Analysis) -setup to the University of Surrey, UK. The sales price was over 0.5 M€. Equipment sales are a significant step for the university. The revenue derived from the sales can be used to fund research, while experiments relating to building the new devices also result in new research publications.

The income from such commercial sales enables the Department of Physics, for example, to employ a postgraduate student for the research team who have spent their time in commercial activities. The sales activities expand the funding base for the University's research profile, which largely builds on funding from different donors, such as the Academy of Finland.

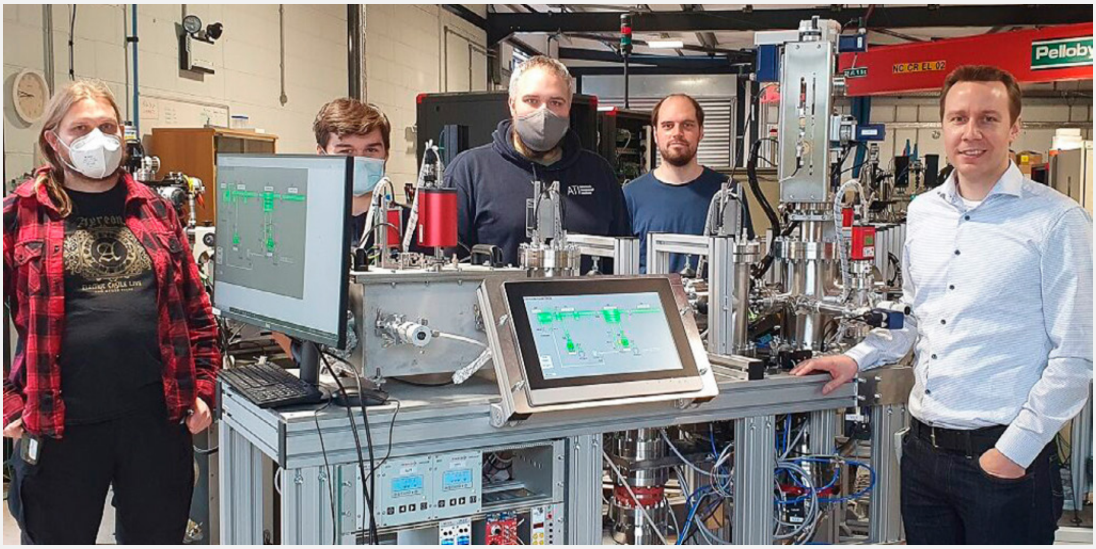
The Dean of the Faculty of Mathematics and Science of the University of Jyväskylä **Mikko Mönkkönen** was also satisfied with the sales:
"This is important for us from the point of view of strategic partnerships, but also financially. All revenues from such sales allow financial headroom for sustaining infrastructure. In addition, it helps our researchers to maintain world-class expertise in technological development."

The device sold to the University of Surrey is a ToF-ERDA (Time-of-flight elastic recoil detection analysis) recoil spectrometer, a research device for accelerator-based material physics. The core output data from such a tool are quantitative elemental depth profiles of all elements, including hydrogen. The device consists of a beamline section, a measuring chamber, a time-of-flight detector, an energy detector, a data collection system and full automation for different manipulation and vacuum devices.

In the autumn 2022 a new order was received for an even larger Tof-ERD spectrometer delivery to the Slovak University of Technology, Bratislava - Faculty of Materials Science and Technology in Trnava. The contract price for the delivery of such a state-of-the-art tool was 0.75 M€.

MEASUREMENT SERVICES AND PROJECT RESEARCH

One of the most traditional industrial collaborations has been measurement services, for other universities, institutes and industrial partners as well. In the Accelerator Laboratory, this has been done mostly by ion beam analysis methods and providing quantitative information of elemental depth profiles of different coatings – typically for integrated circuits, solar panels or battery materials. X-ray tomography and the equipment in the Nanoscience Center cleanroom facilities have also been used for individual requests of collaboration and research-for-hire for the industry by several research groups. Additionally, MSc thesis works have been used in a form of an industrial collaboration, and during 2022, one such thesis work opened a new window to even a larger Business Finland funded project – providing important research funding also for the department.



↑ Figure 1. Pierre Couture (2nd right), Matthew Sharpe (3rd right) and Callum McAleese (2nd left) from the University of Surrey and Jaakko Julin (left) and Mikko Laitinen (right) were pleased with the delivery of the new ToF-ERD tool to the University of Surrey, UK.

TEACHER EDUCATION AND PHYSICS EDUCATION RESEARCH

Professor Pekka Koskinen
Senior Lecturer Antti Lehtinen
Postdoctoral Researcher Pekka Pirinen

Our group is an assembly of physicists, physics teacher educators and physics education researchers. The group contributes to the department's physics education research and teaching development activities, which have gained momentum and attention during recent years. We work in collaboration with the Departments of Education and Teacher Education.

https://www.jyu.fi/en/research-groups/physics-education-research-and-physics-teacher-education

FINNISH HIGH SCHOOLERS' GENDERED MOTIVATIONS TO STUDY PHYSICS

The number of overall students and especially female students taking part in the matriculation exam in physics has increased significantly in recent years. At the same time, the number of females enrolling into Finnish physics departments has not increased at the same rate. Ville Heinonen set out to study this phenomenon in his master's thesis which was also the first article-based [1] master's thesis ever from the field of physics education at JYFL. The results showed that male high schoolers had higher intrinsic and extrinsic motivation to study physics. Female high schoolers motivations to study physics were related more often to opportunities outside the field of physics, e.g.: *"I study physics for the high entry points* [for university entrance], *to get into business school."*

It seems that as the role of physics (as the largest non-mathematical and non-language subject in high school) in the university entrance system has had the effect of increasing the number of females studying physics but many of them are not planning to study physics further.

IMPACT OF TRADITIONAL JYFL LAB INSTRUCTION ON STUDENTS' CRITICAL THINKING SKILLS

In anticipation of coming curriculum reform at JYFL and ongoing revolution in the student lab (see the next chapter), we conducted a baseline study on physics students' critical thinking skills [2]. More precisely, we focused on how the students' ability to evaluate models and methods, and to suggest next steps for an investigation, develops. We collected data using the Physics Lab Inventory of Critical thinking (PLIC), which we translated into Finnish and validated. When the students were enrolled into traditional labs, there was no statistically significant change in students' critical thinking skills over the course of two semesters. However, a small decrease in the perceived usefulness of laboratory work was observed. The results of this study serve as a reference point against which PLIC data collected over the pilot runs of new lab courses in the academic years (2022–2023) and (2023–2024) can be reflected upon.

Selected publications

[1] V. Heinonen, A. Lehtinen and A. Kankainen (2022). Lukiolaisten motivaatio opiskella fysiikkaa: onko tässä eroja miesten ja naisten välillä?, *FMSERA Journal*, 5(1), 18–30. *https://journal.fi/fmsera/article/view/115439*

[2] P. Pirinen, A. Lehtinen, and N. G. Holmes (2023). Impact of traditional physics lab instruction on students' critical thinking skills in a Finnish context. *Eur. J. Phys.* 44(3), 035702. *https://doi.org/10.1088/1361-6404/acc143*.

PHYSICS EDUCATION

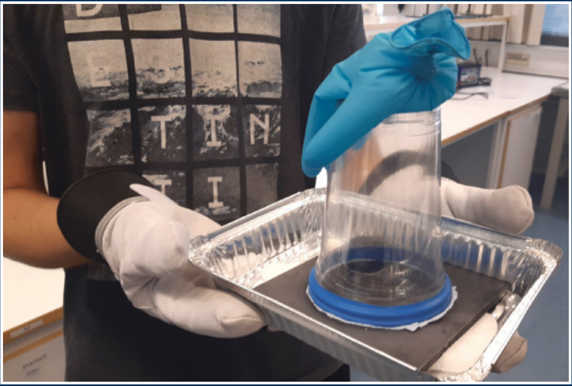
Professor Pekka Koskinen
University Teacher Jussi Maunuksela
Senior Lecturers Antti Lehtinen and Sami Räsänen
Academy Research Fellow Heikki Mäntysaari
Postdoctoral Researcher Pekka Pirinen

REVOLUTION IN THE STUDENT LABORATORY

Traditionally, laboratory instruction involves providing the student with strict recipes to conduct experiments and report their results. However, research has shown that this tradition is inefficient for learning physics, mastering laboratory skills, or learning the process of doing science. At our department, student independence and the lack of a formal schedule has also often resulted in delayed lab reports (sometimes years!) and consequently lagging lab courses and graduation. The delays also burden students.

Therefore, to address these issues, a couple of years ago we had started the planning of a complete overhaul of the student labs. This planning culminated in the first revised lab course pilot in the fall 2022. The central elements in the revised format include a strict scheduling, obligatory participation, group work, and versatile assessment. The role of lab reports was overturned. Central was also a profound change in the role of the laboratory assistant, who changed from being a technical assistant to being a proper teacher of experimental skills. Our guiding principle was to have as little course work after (or before) the groups' meetings as possible, so that most of the work and the assessment would take place during the contact teaching.

The outcomes from the pilot were encouraging. The course had 79 participants of whom 74 completed the course by the end of January 2023, resulting in a completion rate of 94 %—in practice, all students that actively participated in the course also passed it. For comparison, during 2017–2021 the rate ranged from 41 % to 72 %. Even the student feedback was highly positive. These encouraging results are useful for motivating us to plan and realise the four remaining lab courses.



↑ Figure 1: Students designed their bubble chamber.

INTERNATIONAL PHYSICS OLYMPIADS

The department has a long tradition for selecting and training advanced upper secondary school students to represent Finland in international physics competitions. In 2022, around 20 students from Finland participated in the Nordic-Baltic Physics Olympiad in Tallinn, with a team of five students selected to the 6th European Physics Olympiad (EuPhO) held in Slovenia. At the EuPhO the Finnish team obtained one bronze medal and two honorable mentions. Unfortunately, the traditional highlight of the year, the International Physics Olympiad, was canceled due to the initial plan to have it in Belarus. At the Physics department we also organized a training camp where the students could prepare for the experimental tasks they encounter at these international competitions.

RESEARCHERS' NIGHT

Senior Researchers Janne Pakarinen and Arttu Miettinen

The general public across all demographic groups wandered in the laboratories of the Department of Physics on the last Friday of September. After the COVID-19 pandemic, the Researchers' Night public outreach event was back with open arms and doors for people hungry to learn about science. This was a much sought after move following previous year's semi-virtual event. After all, outreach is all about communications in person rather than interactions through webcams.

Like earlier, the event was University-wide and consisted of a large number of various demonstrations, workshops, and lectures. The Department of Physics was again one of the most popular sites with a diverse program: there were physics workshops for pre-school children, tours in the Accelerator Laboratory, a possibility to discuss the origins of the universe with cosmologists, and imaging and visualization workshops to name a few attractions. Around 1 400 visitors found their way to the Department of Physics to meet tens of researchers at different career stages.

↑ Figure 1. Taneli Kalvas explaining the differences between infrared and visible light for future physicists in the Accelerator Laboratory.

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