JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

**ANNUAL REPORT 2023**
**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.

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# STATISTICAL DATA FROM 2023

**166**
PERSONNEL

- Professors, Assistant professors and Associate professors **20**
- Senior lecturers, Senior Researchers **24**
- Postdoctoral researchers **29**
- Doctoral Researchers **40**
- Technical staff **25**
- ERC grantees **1,5**
- \+ Several research assistants (MSc students)

• Personnel counted in person-years

**~340**
UNDERGRADUATE STUDENTS
of which new students **68**
Doctoral students **68**

**15**
BSC DEGREES

**30**
MSC DEGREES
of which RADMEP students **11**

**18**
PHD DEGREES

**322**
NUMBER OF FOREIGN VISITORS
**399**
in visits

| ~260 | ~230 | ~20 | ~10 |
|---|---|---|---|
| Peer reviewed publications (A) | A1-A3 articles | Conference Proceedings A4 | Other publications |

**16.0**
FUNDING (million €)

- Basic financing **8.6**
- Sales (contract research) **1.7**
- Income according to separate laws (mainly EU funding) **1.8**
- Government grants **3.6**
- Other income **0.2**

## CONTENTS




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Timo Sajavaara

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# Preface

20
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ANNUAL REPORT
**Department of Physics**

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JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

**This Annual Report provides an extensive summary of the activities at the Department of Physics during the year 2023.**

The Department of Physics conducts experimental and theoretical research in materials physics, particle physics, and nuclear physics. The Accelerator Laboratory serves as a significant research infrastructure for experimental nuclear physics, while particle physics research maintains strong connections to experiments conducted at CERN. Additionally, materials physics research is concentrated at the interdisciplinary Nanoscience Center. Beyond research activities, the Department of Physics is one of Finland's largest institutions offering BSc, MSc, and PhD degrees in physics.

Year 2023 was the first full year after 2019 without Covid-19 restrictions. Researchers returned to their offices, and students returned to campus. One could say that things went back to normal, although many good developments have been permanently adapted. For instance, international one-day meetings have now permanently been moved to Zoom and Teams, and prerecorded lectures can be used as additional material in courses even if normal lecturing takes place. The number of PhD graduates in 2023 was high (18), which is surely a result of more intensive supervision after the pandemic. A similar jump is expected in the MSc graduates, albeit with a small delay.

The Centre of Excellence in Quark Matter started in 2022, and in 2023, it was working at full strength. On top of the CoE, particle physics researcher Heikki Mäntysaari was rewarded in November with an ERC consolidator grant for his project titled 'Shining Light on Saturated Gluons.' The project focuses on the strong interaction between the ultimate components of matter: quarks and gluons. In 2023, decisions were made for new Research Council of Finland flagship projects. One of the three projects coming to our university, The Finnish Quantum Flagship, has strong participation from the Physics department. The flagship's activities in Jyväskylä are led by Professor Tero Heikkilä. The Accelerator Laboratory retained its national task as a center of expertise and training site for accelerator technology and radiation from 2024 to 2027. Additionally, the Department of Physics received several grants from the Research Council of Finland, improving our faculty's otherwise tight economic situation.

Two associate professors, Jussi Toppari and Juha Muhonen, both working in the field of experimental materials physics in NSC, were promoted to a full professorship in 2023. Closer to the end of the year one long term wish became reality, when Jenni Toivanen started working in the Physics and Chemistry departments. Her job title is coordinator and her task is to support in the management of these two departments.

In 2023, our department lost more than a hundred years of JYFL experience when senior scientist Wladyslaw Trzaska, chief engineer Pauli Heikkinen, and laboratory technician Martti Hytönen retired. They all had an important role in the success of the Physics Department and especially the Accelerator Laboratory. Professor Anu Kankainen was awarded in autumn 2023 the prestigious Väisälä prize for her nuclear astrophysics research. The first step of Ylistö renovation, NSC clean room extension was finally completed in spring 2023. The next step is the modification of the Department of Biological and Environmental Science and new premises for the Chemistry Department. This work should be completed in summer 2026. The renovation timeline for the Physics Department has not been fixed, but more concrete plans should be available in 2024.

**Timo Sajavaara**
HEAD OF DEPARTMENT

# THE YEAR 2023 AT THE NSC

**Professor Jussi Toppari**
**Scientific Vice Director of Nanoscience Center**

The year 2023 started lively in NSC. At the very beginning of the year the first part of the Ylistö renovation, *i.e.*, the new clean room extension was finished and taken into use. The first device installed in the new premises was the new molecular beam epitaxy (MBE) device which is used to produce samples for new STM. After that the Helium Ion Microscope was installed into its new quiet location, and slowly the new area has been filling with multiple instruments.

The biannual meeting of NSC's Internal Advisory Board (IAB) took place in 2023. The event was held live for the first time after the COVID break and was organized in conjunction with the annual Nanoscience Days conference. The event went smoothly with good atmosphere. NSC got great evaluations but more importantly also essential advices to improve its activities. Also the internal event WeNSC was organized again in Konnevesi research station.

During 2023 two new ERC grants, consolidator and starting, were obtained in NSC. However, this time not for physics but in biology and chemistry. In general 2023 was a good year for NSC and nanophysics, but people in NSC were already busy preparing the next year, which will be the celebration of 20-year birthday of NSC.

Looking forward to 2024!

# THERMAL NANOPHYSICS

**Professor Ilari Maasilta**

**The group is one of the main users of the nanoscience center (NSC) nanofabrication and cryogenic 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.

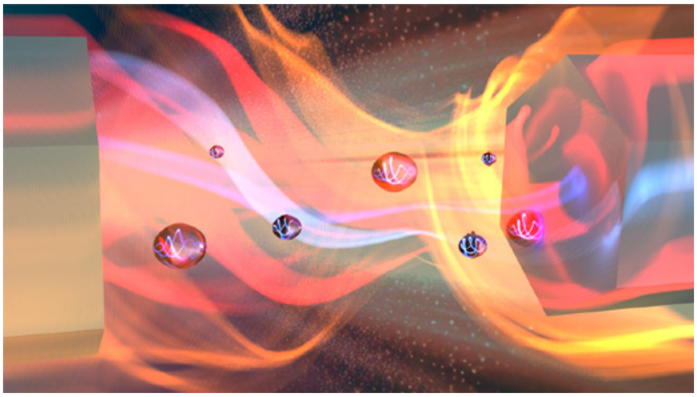
*https://www.jyu.fi/en/research-groups/thermal-nanophysics-and-superconducting-devices*

### NANOSCALE THERMAL TRANSPORT

Year 2023 continued with a strong focus on nanoscale thermal transport, supported by the Academy of Finland. The two main sub-areas advanced are i) phonon tunneling across vacuum and ii) phononic crystals.

For phonon tunneling, we continued our theoretical and computational efforts to explain how acoustic waves (phonons) can jump, or "tunnel" across vacuum from one piezoelectric crystal to another. This effect is made possible by the electric field associated with the wave, and takes place as long as the size of the vacuum gap is smaller than the wavelength. This effect is very general and works from the audio range of frequencies (Hz-kHz) to ultrasound (MHz) and all the way to hypersound (GHz), as long as the vacuum gap is made smaller with increasing frequency, down to nanoscale for hypersound. In 2023, we advanced the theory and discovered to our surprise that conditions exist where the sound wave (phonon) can tunnel completely, with probability one, without any reflections! [Geng2023a] Such conditions correspond physically to the excitation of surface waves on both surfaces. Ongoing work addresses the impact of this phonon tunneling on the heat transfer, as a new channel of near-field thermal "radiation".

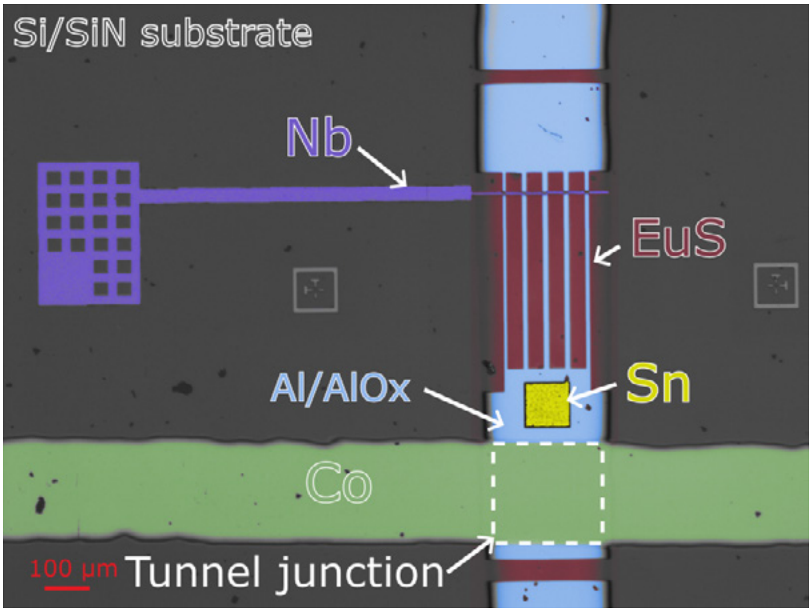
In the research on phononic crystals, in addition to continuing our experimental research on the topic, we highlight another theoretical/numerical study [Puurtinen2023]. In that study, we developed an analytic theory for a thermal metamaterial which can be used to strongly modify the heat capacity of a plate using a periodic holey structure. The work describes the thermal response in the temperature range where the holey material looks continuous (phonon wavelengths much longer than the period), but with modified elastic properties and density because of the structuring. The modified elastic properties in turn change the vibrational spectrum of the material (phonon energies), which directly affects the capacity to store heat.



← Figure 1. Artistic view 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 related to quantum technology continued in 2023. One major development in 2023 was the start of the Finnish Quantum Flagship within the Academy of Finland Flagship funding scheme, where our group is a member in the program developing novel quantum devices, focusing on superconducting qubit and sensor development. Another event was the conclusion of the European SUPERTED EU FET-open project, where important steps were taken to develop a novel sensitive superconductor-ferromagnet X-ray detector and its measurement setup. A prototype detector was fabricated in-house in collaboration with CSIC in Spain, and its performance was analyzed theoretically to be very promising, on par with the most sensitive existing detector technologies in terms of energy resolution, but potentially achieving faster count rates [Geng2023b].




↑ Figure 2. Fake-color optical micrograph of a SUPERTED X-ray calorimeter. A superconductor–ferromagnet heterojunction area is shown with the white dashed line, consisting of layers of Si/SiN/EuS/Al/AlOx/Co from the bottom to the top. A Sn absorber is placed to the side of the junction, contacting the Al lead directly.

[Geng2023a] Z. Geng and I. J. Maasilta, *Complete tunneling of acoustic waves between piezoelectric crystals*, Communications Physics 6, 178 (2023)

[Puurtinen2023] T. A. Puurtinen and I. J. Maasilta, *Effective medium theory for the low-temperature heat capacity of a metasolid plate*, Communications Materials 4, 1 (2023)

[Geng2023b] Z. Geng et al., *Superconductor-ferromagnet hybrids for non-reciprocal electronics and detectors*, Supercond. Sci. Technol. 36, 123001 (2023)

# MOLECULAR TECHNOLOGY

**Professor Markus Ahlskog**

**The Molecular Technology group studies primarily the experimental electronic and mechanical properties of carbon nanotubes and devices that are based on them, and both fundamental and applied aspects**. The research has extensively explored the basic electronic transport properties of high quality multiwalled carbon nanotubes (MWNT).

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

### ELECTRONIC PROPERTIES OF MULTIWALLED CARBON NANOTUBES

We have investigated arc-discharge synthesized multiwalled carbon nanotubes (MWNT), which are of excellent quality compared to the more common CVD-synthesized ones. They have capability for all the proven quantum transport properties of single walled nanotubes, and, in addition, important possibilities stemming from the electronic interactions between adjacent layers, which again are intensively studied in bilayer graphene systems. We observe in MWNTs regularly negative differential resistance (Fig.1(a)), which can be explained as due to the involvement of the next inner layer in the conduction at modest bias voltages. Our model for the transport characteristics builds on a tunnelling resistance between the outer and second layer of the MWNT [1].

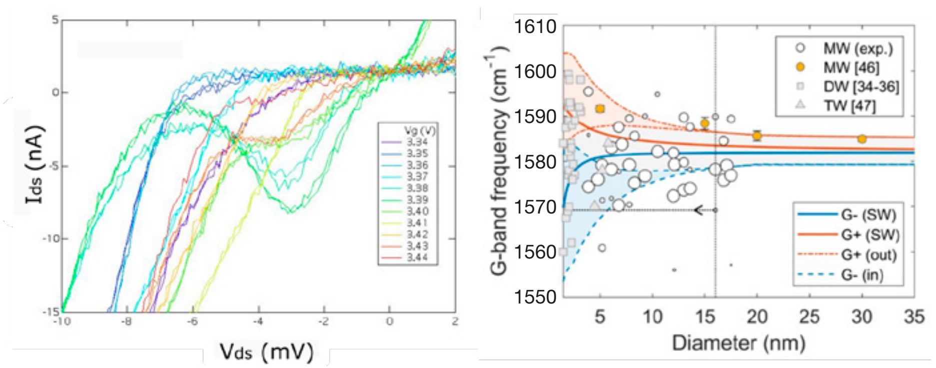
The complicated interlayer van der Waals (vdW) interactions can be investigated in individual MWNTs, prepared by our on-chip purification scheme. Our collaborators have with polarized Raman imaging and spectroscopy observed the splitting of the Raman-active *G*-band group (Fig 1b)), describing it in terms of the variation of inter-layer mechanical vdW coupling as a function of diameter and interlayer distance in the probed MWNTs [2].

### References

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

[2] 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) Current vs. bias voltage measured in an individual MWNT at different gate voltages (inset). A strong behavior of negative differential resistance is seen. b): Dependence of G-band frequency in MWNTs on diameter. Open circles correspond to the fitted G-band frequencies from the experimental data. Other data from literature is included. The calculated deviation in the G− frequency of the inner layer and G+ frequency of the outer layer due to the large spread of interlayer distance values in MWNTs, are represented by the dashed blue and dashed-dotted orange curves, respectively.



# MOLECULAR ELECTRONICS AND PLASMONICS

**Professor Jussi Toppari**

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

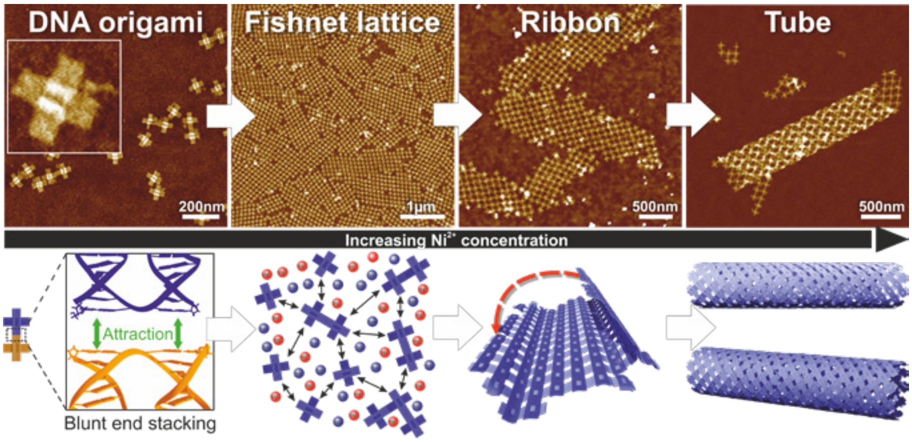
- *Structural DNA-nanotechnology*. Utilization of self-assembled DNA structures, like DNA origami, and their modifications in fabrication of electrical and optical/plasmonic nanodevices.
- *Strong light-matter coupling*. Strong interaction of photoactive molecules with confined light, like surface plasmons and cavity photons, creates new hybrid light-matter states, i.e., polaritons, which provide a promising paradigm for controlling photochemical reactions (polariton chemistry) or transfer energy in molecular level.

*https://r.jyu.fi/mepl*

#### TOWARDS METAMATERIALS BY DNA SELF-ASSEMBLY

On our DNA nanotechnology research, we have concentrated during the last few years on realization of self-assembled fishnet type metamaterial. These materials have been shown to possess negative refractive index in infra-red region, and very recently the operation range has been pushed to the red part of the visible spectrum. The realization of this requires very precise and time-consuming lithography, such as e-beam lithography, which is still not exact enough to reach the blue range of the visible spectrum. 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 blue range fishnet metamaterials in low-cost manner.

To be able to apply DALI or basically any modern microfabrication method, the origami self-assemble needs to be realized on silicon, instead of mica surface, which has been used in all the demonstrations so far but is not compatible with any microfabrication techniques. During 2023 we have successfully demonstrated the assembly of a 2D fishnet-type lattice on a silicon substrate [1]. 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 1 [2]. 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 1. Schematic view of the formation of the hierarchical nanostructures using the cross-shaped DNA-origami with blunt-end stacking interaction between them to form fishnet-type lattices on surface (low nickel) and in solution (high nickel). The lower row sketches the behavior of origamis with increasing $Ni^{2+}$ concentration, while the upper row shows corresponding AFM images.

## SURFACE EXCITONS IN ORGANIC THIN FILMS

Organic thin film based excitonic nanostructures are of a great interest in modern resonant nanophotonics as a promising alternative for plasmonic systems. Such nanostructures sustain propagating and localized surface exciton modes which can be exploited in refractive index sensing and near-field enhanced spectroscopy. To realize these surface excitonic modes and to enhance their optical performance, the concentration of the excitonic molecules present in the organic thin film has to be quite high so that a large oscillator strength can be achieved. Unfortunately, this often results in a broadening of the material response which might prevent achieving the very goal. Therefore, systematic and in-depth studies are needed on the molecular concentration dependence of the surface excitonic modes to acquire optimal performance from them.

We have studied the effect of molecular concentration in terms of oscillator strength and Lorentzian broadening on various surface excitonic modes and evaluated the performance of these modes in terms of sensing, like sensitivity and figure of merit, as well as near-field enhancement, like enhancement factor and field confinement [3]. Our numerical FDTD calculations reveal that, in general, an increase in oscillator strength enhances the performance of the surface excitonic modes while a broadening degrades that as a counteracting effect. Most of all, this demonstrates that the optical performance of an excitonic system is tunable via molecular concentration unlike the plasmonic systems. Moreover, different surface excitonic modes show different degrees of tunability and equivalency in performance when compared to plasmons in metals (silver and gold).

## COLLABORATIONS: CORONAVIRUSES AND ION BEAMS

In 2022 we also obtained some nice results from several of our collaborations. For example, from development of antiviral plastic surface against human coronaviruses where we imaged these viruses with several different microscopes on variety of substrates [4], and from shaping of plasmonic nanoparticles with heavy ion irradiation [5].

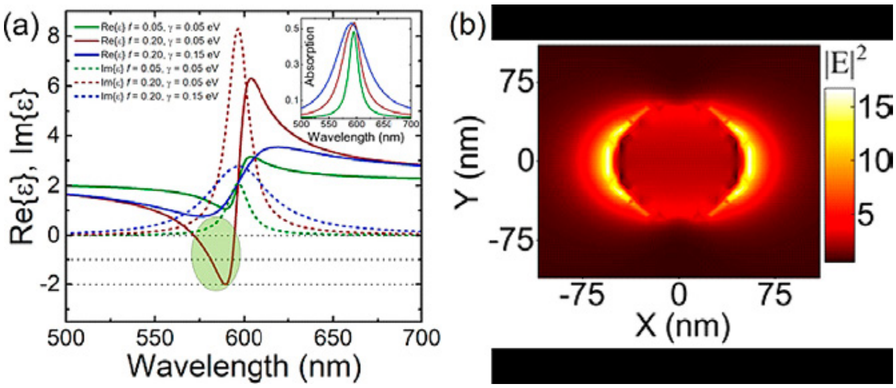

[1] K. Tapio, C. Kielar, J.M. Parikka, A. Keller, H. Järvinen, K. Fahmy, J.J. Toppari, *Large scale formation of DNA origami lattices on silicon*, Chem. Mater., 35, 1961 (2023).

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

[3] A. Dutta, J.J. Toppari, *Effect of molecular concentration on excitonic nanostructure based refractive index sensing and near-field enhanced spectroscopy*, Opt. Mat. Exp. 13, 2426 (2023).

[4] S. Shroff, M. Haapakoski, K. Tapio, M. Laajala, M. Leppänen, Z. Plavec, A. Haapala, S.J. Butcher, J.A. Ihalainen, J.J. Toppari, and V. Marjomäki, "Antiviral action of a functionalized plastic surface against human coronaviruses", Microbiology Spectrum (2024).

[5] S. Korkos, K. Arstila, K. Tapio, S. Kinnunen, J.J. Toppari, T. Sajavaara, *Elongation and plasmonic activity of embedded metal nanoparticles following heavy ion irradiation*, RSC Adv., 13, 5851(2023).


↑ Figure 2. (a) The real (solid curves) and imaginary (dashed curves) parts of the dielectric function (ε) of a 60 nm thick PVA layer with different amounts of TDBC molecular aggregates. Higher amount induces higher absorption (inset) and Lorentz oscillator strength (*f*), which is usually accompanied with increased linewidth (*γ*). The green spot on the figure depicts the region where *Re*{*ε*} < 0 and |*Im*{*ε*}| < |*Re*{*ε*}| which allows the existence of surface exciton modes. (b) Spatial distribution of near field enhancement around a TDBC-PVA nanosphere having a diameter of 100 nm, *f* = 0.5, and *γ* = 0.05 eV, computed by FDTD method. The surface exciton resonance of the nanosphere is at wavelength 569 nm.

# 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 novel quantum devices and in studying the fundamental quantum phenomena.**

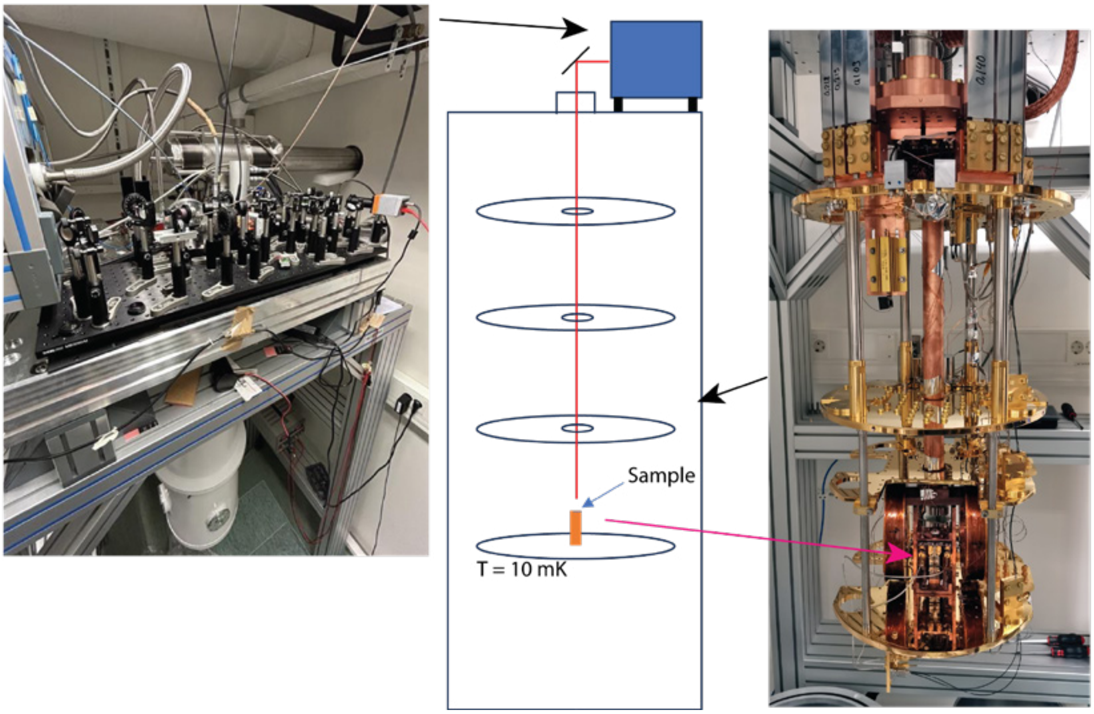
Quantum technologies will be one of the defining technologies of our future. Quantum mechanical phenomena enable creating new kinds of sensors, communication methods and computers. The realization of a quantum computer would be a major shift in the computing capabilities of the humankind, and we can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

*www.jyu.fi/quantum-technologies*

### OPTOMECHANICS USING SILICON NANOSTRUCTURES

During the year, our optomechanical efforts moved forward. We published a paper on our measurement method, where we continuously sweep the homodyne interferometer phase and hence average over all the quadratures of the measured signal [1]. This has specific advantages for the case when the signal includes both the resonant signal and some unspecified non-resonant background, which is generally always the case with the nanophotonics structures. This was a collaboration with Ewold Verhagen's group at AMOLF.

The year also saw us moving into millikelvin optomechanical measurements as the interferometric measurement setup build around the Bluefors dilution refrigerators was finished.  This is shown in Figure 1. We have built an optical breadboard on top of the refrigerator, where the laser light is guided in via a window and travels to a focusing lens fixed at the low temperature parts. Below lies the sample on top of a piezo stage, allowing us to address multiple devices on chip. We have a camera on top of the fridge to locate our samples. First measurements have been performed and we are now analyzing data.




↑ Figure 1. Experimental setup for millikelvin optomechanical experiments. We have built an optical homodyne interferometer on top of a dilution refrigerator. The laser beam is guided to the cold experimental space in free space, through several thermalized mirrors. At 10 mK temperature we have a focusing lens and a moving stage as well as a homebuild superconducting magnet.

#### HYBRID OPTO-ELECTRICAL READOUT OF SPIN STATES IN SILICON

One of the directions in the group is to advance the readout of silicon spin states via a donor bound exciton transition. This readout method has been shown before for large ensembles, but we aim to scale it down to single spin level, by combining with suitable charge detectors. These charge detectors are planned to be silicon quantum dots, realized by the new Finnish start-up Semiqon Oy (see next section). On our way to this goal, we studied the general properties of the exciton transitions and found out some interesting physics on how strain affects the transitions [2].

#### NEW OPENINGS FOR COMMERCIAL INTERACTION

There were 2 new major openings regarding commercial interaction for the group:

1. During 2023 Prof. Muhonen headed a successful Business Finland application to develop a new joint private-public infrastructure environment for the research and development of quantum technology platforms. The new infrastructure will specifically target the activities involving semiconductor spin qubits for which the infrastructure in Finland is still underdeveloped. Semiqon Oy was involved in the application as a committed user to the final infrastructure. The infrastructure will be build during 2024–2025 and opened to external users late 2025.
2. A official joint research project was started with Semiqon Oy, relating to their quantum dot devices. Semiqon is a spin-off company from VTT, commercializing the silicon quantum dot fabrication know-how of VTT, with the aim to build a scalable solution for quantum processing. Our group's main interest is in combining these devices with our other research projects for both individual spin readout and for creating hybrid devices. At the moment the collaboration revolves around measurements of the quantum dot devices and providing feedback for improving them.

[1] Giada R La Gala, Arvind Shankar Kumar, Rick Leijssen, Ewold Verhagen, Juha T Muhonen, *Quadrature-Averaged Homodyne Detection for Estimating Cavity Parameters*, Phys. Rev. Applied 19, 064006 (2023)

[2] Teemu Loippo, Antti Kanniainen, Juha T Muhonen, *Strain effects in phosphorus bound exciton transitions in silicon*, Phys. Rev. Materials 7, 016202 (2023)

# SYNTHETIC QUANTUM MATERIALS

**Associate professor Kezilebieke Shawulienu**

**We are a dedicated research group at the University of Jyväskylä focused on investigating synthetic quantum materials**.

Our research revolves around studying materials that showcase intriguing and unconventional phases of quantum matter, including topological superconductivity, topological insulators, and collective behaviors of interacting electrons in low-dimensional systems. Additionally, we delve into the spin properties of atoms and molecules on various surfaces.

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

To engineer customized quantum materials, we employ molecular beam epitaxy techniques, allowing us to meticulously grow artificial materials layer by layer. Once synthesized, we employ cutting-edge low-temperature scanning tunneling microscopy (LT-STM) and spectroscopy (STS) techniques to investigate the electronic and magnetic characteristics of our synthesized materials.

In addition to our ongoing research efforts, our long-term objective is to develop a comprehensive protocol for synthesizing multifunctional and reprogrammable quantum materials. These materials hold immense potential for utilization in future electronic devices, specifically for quantum information technology. By successfully achieving this goal, we aim to contribute significantly to the advancement of quantum computing and related fields, paving the way for revolutionary breakthroughs in information processing and communication.

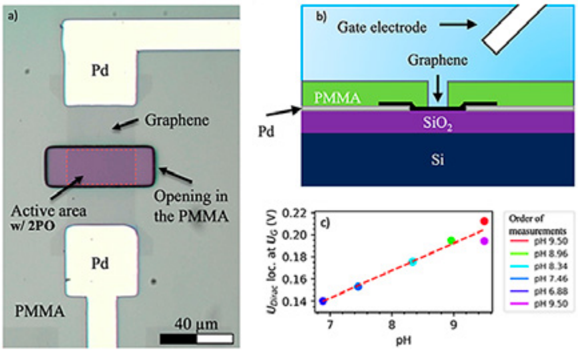
# NANOCARBON LABORATORY

**Senior Researcher Andreas Johansson**

**Novel nanomaterials are developing at a rapid pace as they offer new possibilities for applications in electronics, optics, nano-mechanics and medicine. We study the synthesis and modification of especially carbon-based nanostructures, often using graphene as the starting point.** New fabrication techniques are developed using cleanroom techniques as well as femtosecond laser processing, and the resulting nanostructures are incorporated in device geometries that benefit from having nanometer precision in critical features. Applications range from low temperature electronic transport in 2.5 dimensional structures to area-selective ALD deposition, microfluidic sorting of nano- and micrometer objects, and in-vivo neuronal sensors of graphene. Our projects are often interdisciplinary in nature, with groups from biology, chemistry and physics working together.

*https://www.jyu.fi/en/research-groups/nanocarbon-laboratory*

During 2023 our focus was in two research directions, one being the development of a graphene-based pH-sensor in the micrometer scale. It resulted in a graphene field-effect transistor sensitized by femtosecond laser exposure (Figure 1) to induce two-photon oxidation (2PO) in the active sensor area [1]. With 2PO treatment the pH-sensing was tunable towards better performance. The next target is to implement the pH-sensor into microfluidic environments to study biological samples.




↑ Figure 1. Graphene pH sensor. a) Optical image of the graphene sensor. b) Schematic of the device cross-section, depicting the liquid gate electrode at top right. c) Dirac point position as a function of pH, acquired from transfer characteristics of the graphene FET.

The second research direction was exploring graphene functionalization strategies to achieve an environment preferential to peripheral neurons. It is part of a larger project targeting biocompatible graphene-based neuronal sensors able to work seamlessly in-vivo. Here we published one study on the compatibility of 2PO functionalization of the graphene surface before extracellular matrix scaffolding via hydrogelation on top of the graphene device [2]. Another study was made on a hybrid hydrogel of Fmoc-F and graphene oxide (GO) flakes. The addition of GO enhanced the gelation and resulted in promising antimicrobial properties [3].

[1] Aku Lampinen, Erich See, Aleksei Emelianov, Pasi Myllyperkiö, Andreas Johansson and Mika Pettersson, *Laser-induced tuning of graphene field-effect transistors for pH sensing*, Phys. Chem. Chem. Phys. 25, 10778 (2023)

[2] Johanna Schirmer, Romain Chevigny, Aleksei Emelianov, Eero Hulkko, Andreas Johansson, Pasi Myllyperkiö, Efstratios D. Sitsanidis, Maija Nissinen and Mika Pettersson, *Diversity at the nanoscale: laser-oxidation of single-layer graphene affects Fmoc-phenylalanine surface-mediated self-assembly*, Phys. Chem. Chem. Phys. 25, 8725 (2023)

[3] Efstratios D. Sitsanidis, Lara A. L. Dutra, Johanna Schirmer, Romain Chevigny, Manu Lahtinen, Andreas Johansson, Carmen C. Piras, David K. Smith, Marja Tiirola, Mika Pettersson, and Maija Nissinen, *Probing the Gelation Synergies and Anti-Escherichia coli Activity of Fmoc-Phenylalanine/Graphene Oxide Hybrid Hydrogel*, ACS Omega 8, 10225–10234 (2023)

# 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 modeling, experimental fluid mechanics and rheology, as well as their applications in various industrial problems.** The group runs an open-access 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. Examples of the group's research topics include water kinetics in chemo-elastic clays, micro- and nanostructure of engineered biomaterials, and image-based soil structure characterization.

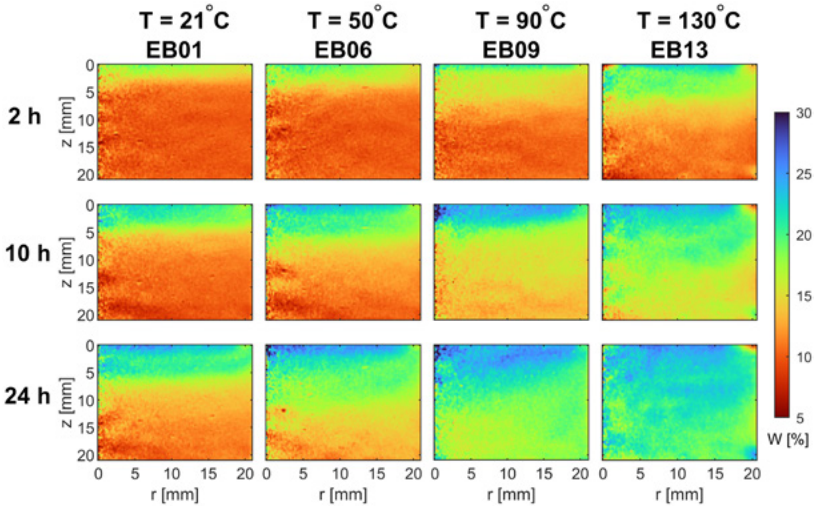
*https://www.jyu.fi/en/research-groups/complex-materials*

In 2023, we were pleased to host Prof. Peter Moonen from UPPA, France, as the opponent for the PhD defense of Tero Harjupatana. Tero continues to work in the Academy of Finland-funded WaterInWood project focusing on the measurement and modeling of water transport properties of wood. In addition to WaterInWood, we started SAGE project focusing on creating a surrogate model of bentonite materials for radioactive waste repository design and optimization, and FLOP project where the fracture networks in bedrock are modeled with the assistance of various imaging technologies including X-ray tomography. Both projects are funded by the SAFER2028 program.

The group started collaborating with the RADiation EFfects facility, and an initial version of a megavoltage tomography system was built. It is based on a medical linear accelerator and features an X-ray spectrum extending up to 15 MeV, enough to penetrate dm-size metallic objects. The spatial resolution of the experimental tomograph is currently around 0.3 mm and might be improved in the future. The device is designed to initially serve the FLOP project and industrial collaboration as described also in section Y[Radiation Effects].

#### MONITORING OF WATER CONTENT AND DRY DENSITY OF SWELLING CLAYS IN HIGH TEMPERATURES

As a part of the EURAD HITEC project, X-ray tomography and 4D image analysis were used to monitor water transport and swelling deformation in compacted sodium-bentonite samples at elevated uniform temperatures in constant volume conditions. The study aimed to assess the temperature dependence of the hydromechanical properties of bentonite and the water transport process in it. The motivation for the study is the safety assessment of the geological final disposal of radioactive waste, as bentonite is planned to be used as a barrier material in several disposal concepts, e.g., in Finland and Sweden. When the waste packages are placed in the repository, they generate heat, which increases the temperature of the surroundings. Therefore, the influence of temperature on the hydromechanical properties of the bentonite barrier must be studied experimentally and by material modeling. The complex materials group used the X-ray tomographic method to obtain experimental data (Figure 1), which can be utilized in the material model development and validation or directly in the safety assessment. During the project, the previously developed method was updated by incorporating some nonstandard correction methods into the image analysis workflow.




← Figure 1. Azimuthal average of the water content of the cylindrical bentonite samples. The 4D evolution of the water content distribution is visualized here at four temperatures and in three instants of time.

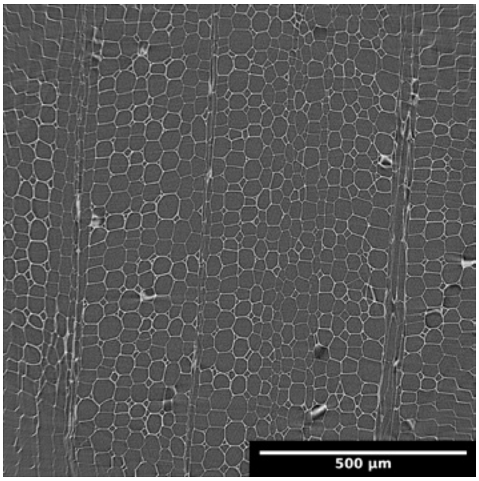
## USER ACTIVITIES IN THE X-RAY TOMOGRAPHY LABORATORY

The X-ray tomography laboratory is open to both academic and industrial users. In 2023, we served several research groups. Some examples of our activities are below.

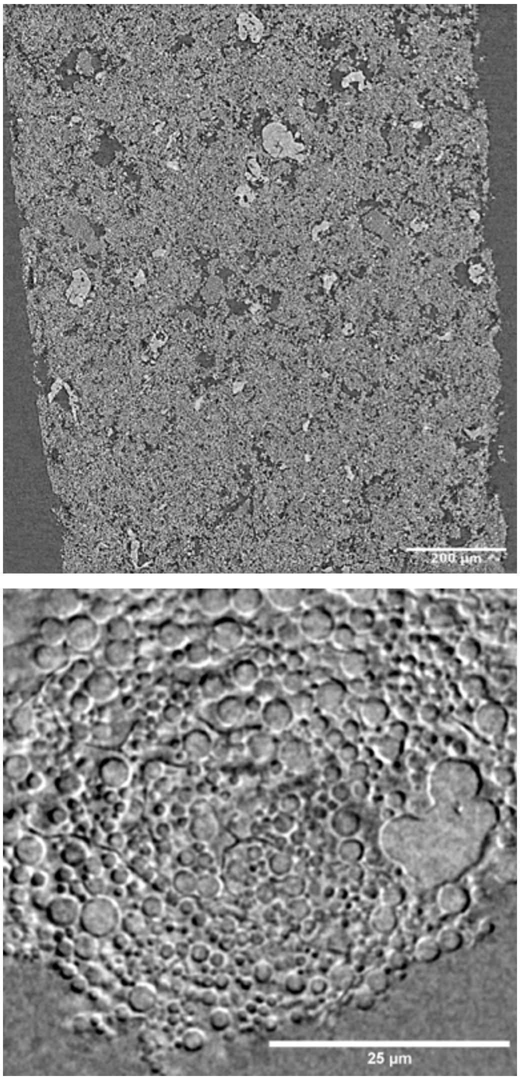
In a project led by the University of Helsinki [1], we used X-ray tomography to find 3D spatial locations of radioactive, insoluble, respirable Cs-bearing microparticles (CsMPs) in samples used to characterize a novel real-time autoradiography system. The new system uses parallel ionization multiplier gaseous detectors, and it is faster than the older technology. The applications are in the detection of CsMPs in nuclear forensic situations such as releases of radioactive materials in nuclear accidents.

Researchers of Aalto University and collaborators characterized their new superblack materials using the devices of the X-ray tomography laboratory [2]. These new materials are made using metal-free delignification and carbonization of wood in high temperatures. The biological structure of wood cells remains in the process and creates vertically aligned carbon microfiber arrays. The light reflectance of the materials is as low as 0.36 % and they are suggested as a surrogate for microfabricated carbon nanotube arrays. Here, X-ray tomography was used to validate the biological origin and dimensions of the micro-geometry for Finite Element reflectance simulations (Figure 2).

In [3], a similar carbonization process was applied to lignin particles made from forest industry side streams. Combined with cellulose nanofibers, a bioink with suitable rheology is obtained. The light reflectance of the dried inks shows three times lower values than commercial black inks. In this work, the nationally unique multi-scale micro- and nanotomography resources of the X-ray tomography laboratory were used to see the macroscopic irregular morphology of the dried bioinks using 1.15 μm and 65 nm resolutions (Figure 3).




↑ Figure 2. Cross-sectional slice through a carbonized and lignified wood sample, showing the remaining wood cell structure.




↑ Figure 3. Microtomography cross-section (on top) and nanotomography cross-section (below) through dried bioink sample showing irregular morphology.

[1] Joyce W. L. Ang, Arthur Bongrand, Samuel Duval, Jérôme Donnard, Joni Parkkonen, Satoshi Utsunomiya, Risto Koivula, Marja Siitari-Kauppi, Gareth T. W. Law. Improved Radio-Cesium Detection Using Quantitative Real-Time Autoradiography, ACS Omega 2023, 8, 25, 22523–22535. *https://doi.org/10.1021/acsomega.3c00728*

[2] Bin Zhao, Xuetong Shi, Sergei Khakalo, Yang Meng, Arttu Miettinen, Tuomas Turpeinen, Shuyi Mi, Zhipei Sun, Alexey Khakalo, Orlando J. Rojas & Bruno D. Mattos. Wood-based superblack, Nature Communications 14, Article number 7875, 2023. *https://doi.org/10.1038/s41467-023-43594-4*

[3] Bruno D. Mattos, Noora Jäntti, Sergei Khakalo, Ya Zhu, Arttu Miettinen, Joni Parkkonen, Alexey Khakalo, Orlando J. Rojas, Mariko Ago. Black Bioinks from Superstructured Carbonized Lignin Particles, Advanced Functional Materials 33(45), 2304867, 2023. *https://doi.org/10.1002/adfm.202304867*

# 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) uses and develops multiple computational methods and machine learning to investigate metal-based nanoparticles whose atomic structure is known or can be modeled to **atomic precision**. Currently we want to understand:

- How do metal nanoparticles work as electrocatalysts?
- How do gold- or silver-based nanoparticles work as sensors in a biological environment?
- How do gold-based nanoparticles work as targeted carriers for cancer drugs?

In 2023, we enlarged our activities supported by two new grants from the Academy of Finland to study photophysics of DNA-stabilized silver nanoclusters and potential use of gold nanoclusters as sensors for chiral biomolecules. We were also invited to write an in-depth review article on properties and applications of noble metal nanoparticles in Nature Reviews Materials, which made the cover of its June 2023 issue [1].

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

The computational nanoscience group. Back row from left: Antti Pihlajamäki, Maria Francisca Matus, Maya Khatun, Marya Sabooni Asre Hazer. Front row from left: Anssi Sikoniemi, Noora Hyttinen, Zohreh Fallah, Sami Malola, Hanna Jääskö.

## THEORY FOR DNA-STABILIZED SILVER NANOCLUSTERS ESTABLISHED

DNA-stabilized silver nanoclusters with 10–30 silver atoms are by construction ideal candidates for biocompatible bright fluorescent emitters, but their electronic structure is not well understood. Here, using density functional theory (DFT), we analyze the ground-state electronic structure and optical absorption of a bright NIR-emitting cluster Ag16Cl2, which is stabilized by two DNA strands of 9-base sequence 5´-CACCTAGCG-3´ and whose atomic structure was very recently confirmed to have two chlorides bound to the silver core [2]. We are able to (i) unambiguously assign the charge of this cluster in aqueous solvent, (ii) analyze the details of silver–DNA interactions and their effect on the cluster charge, (iii) analyze the character of low-energy optical absorption peaks and the involved electron orbitals and make a first assessment on circular dichroism, and (iv) evaluate the suitability of various DFT exchange–correlation functionals via benchmarking to experimental optical data. [3] This work lays out a baseline for all future theoretical work to understand the electronic, chiroptical, and fluorescence properties of these fascinating biocompatible nanostructures.

## GRAPHS AND KERNELIZED LEARNING CAN PREDICT INTERACTION ENERGY BETWEEN HYDROGEN AND GOLD NANOCLUSTER ELECTROCATALYSTS

Understanding hydrogen adsorption on metal nanoparticles is a key prerequisite for designing efficient electrocatalysts for water splitting and the hydrogen evolution reaction. However, this seemingly simple elementary reaction step is affected by several factors arising from the chemical environment at the catalyst, and deciphering the most important contributions to optimal interactions requires numerically heavy electronic structure calculations. Here, we combine graph-based representations of the local atomic environment of hydrogen in copper- and palladium-doped 25-atom gold nanoparticles with several kernel-based machine learning (ML) methods to predict the interaction energy between hydrogen and the nanoparticle catalyst [4]. We demonstrate that simple distance-based kernel models are able to predict the interaction energy within 0.1 eV when trained by reference data from state-of-the-art density functional theory calculations. Analyzing the model performance with respect to attributes of the hydrogen node highlights the locality of hydrogen adsorption. This implies the viability of combining graphs with kernel-based ML models for studying hydrogen chemisorption in complex environment data efficiently.

**Selected publications**


[1] M.F. Matus and H. Häkkinen, "Understanding ligand-protected noble metal nanoclusters at work ", Nature Rev. Mat. 8, 372 (2023).

[2] A. Gonzalez Rosell, S. Malola, R. Guha, N.R. Arevalos, M. Rafik, M. F. Matus, M.E. Goulet, E. Haapaniemi, B.B. Katz, T. Vosch, J. Kondo, H. Häkkinen and S.M. Copp, "Chloride Ligands on DNA-Stabilized Silver Nanoclusters", J. Am. Chem. Soc. 145, 10721 (2023).

[3] S. Malola, M.F. Matus and H. Häkkinen, "Theoretical Analysis of the Electronic Structure and Optical Properties of DNA-Stabilized Silver Cluster Ag16Cl2 in Aqueous Solvent ", J. Phys. Chem. C 127, 16553 (2023).

[4] A. Pihlajamäki, S. Malola, T. Kärkkäinen and H. Häkkinen, "Graphs and kernelized learning applied to interactions of hydrogen with doped gold nanoparticle electrocatalysts", J. Phys. Chem C. 127, 14211 (2023).

# CONDENSED MATTER THEORY

**Professor Tero Heikkilä**

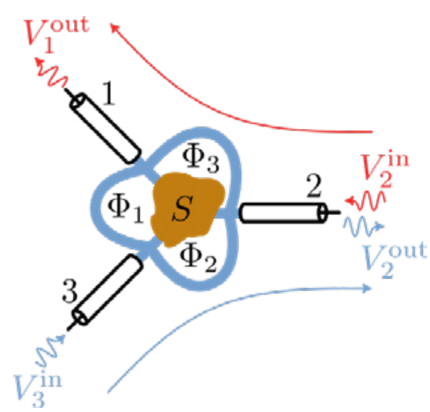
**We study quantum and classical phenomena in small electronic systems, with a focus on superconductivity, magnetism, topological matter and open quantum systems.** Our approach is based on constructing and characterizing the phenomenological low energy theory of quantum systems relevant for the phenomena 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*

## NONRECIPROCITY IN SUPERCONDUCTING RESPONSE

Electrical signals do not necessarily propagate in the same way to opposite directions, which is known as nonreciprocal response. This requires breaking of certain physical symmetries: time-reversal and inversion. In superconducting systems, breaking these symmetries produces the supercurrent diode effect, which is a nonreciprocal effect for DC current. However, it was unclear in what sense the effect would manifest for time-dependent currents. In a recent work [1] we showed how nonreciprocity in microwave electromagnetic response can be realized in nanoscale superconducting Josephson junctions (Figure 1). Nonreciprocal components have important applications in microwave electronics, and finding paths to realize them at nanoscale would be useful for quantum technology, for example in the control electronics of qubits in quantum computers.

We have also recently explored other aspects of dynamical response of superconductors, such as the different types dynamical Hall effects [2] and coupling to the Higgs mode [3] present in certain types of superconductors, and how they could be observed in electromagnetic measurements, or used in sensor applications [4].




↑ Figure 1. Nonreciprocal propagation of electric signals in a multiterminal Josephson junction.

## DISORDER AND SPIN-DEPENDENT INTERACTIONS IN METALS AND SUPERCONDUCTORS

Quantum interference in scattering of electrons from impurities can be either destructive or constructive, leading to weak (anti-)localization corrections to the electrical conductivity. This effect is known to be sensitive to magnetic fields and spin-dependent interactions such as spin-orbit coupling. We showed [5] that the cross-over region from weak to strong disorder can provide detailed information of the spin-dependent interactions, and could be used as a signature identifying their structure.

We have also investigated the interplay of unconventional superconductivity, spin-orbit coupling and disorder in transitional metal dichalcogenide monolayers (TMDs), also known as Ising superconductors [6]. TMDs have been recognized as one of the key platforms for the emerging field of superconducting spintronics, and moreover, they can be combined with other 2D materials in van der Waals heterostructures. In our work, we established the theory of bulk properties of disordered Ising superconductors, which can be directly useful for interpreting recent experiments.

#### MECHANICS OF NANOSCALE MAGNETIC BEAMS

The dynamics of a doubly clamped nanoscale beam made of magnetic material reflects the coupling between its mechanical and magnetic degrees of freedom (Figure 2). In principle, several types of nonlinear coupling are possible, and knowing which of them are present in the system is important for full understanding of the magnetomechanics. We have studied [7] how to distinguish cross-Kerr type coupling in the spectrum of the driven system, and how it can be probed experimentally with two-tone spectroscopy.

**Selected publications**


[1] P. Virtanen and T. T. Heikkilä, "Nonreciprocal Josephson linear response", Phys. Rev. Lett. 132, 046002 (2024)

[2] A. Hijano, S. Vosoughi-nia, F.S. Bergeret, P. Virtanen, T. T. Heikkilä, "Dynamical Hall responses of disordered superconductors", Phys. Rev. B 108, 104506 (2023)

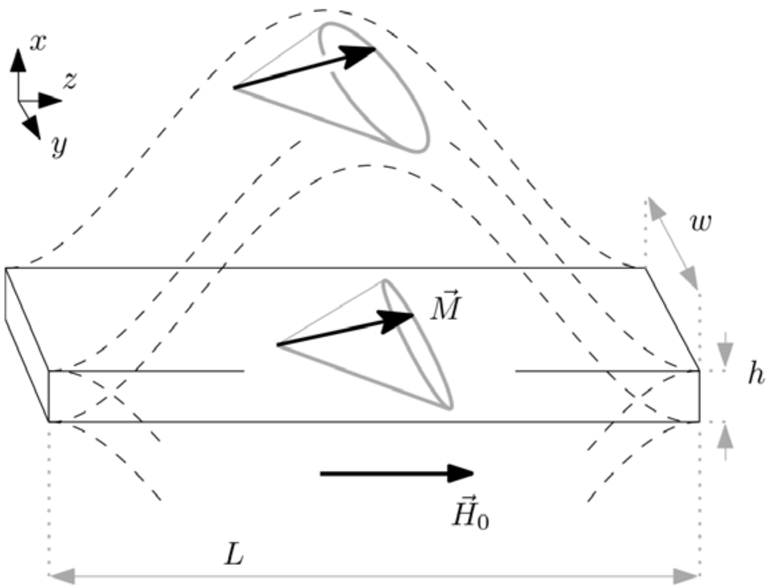
[3] Y. Lu, S. Ilić, R. Ojajärvi, T.T. Heikkilä, F.S. Bergeret, "Reducing the frequency of the Higgs mode in a helical superconductor coupled to an LC circuit", Phys. Rev. B 108, 224517 (2023)

[4] Z. Geng, et al., Supercond. Sci. Tech. 36, 123001 (2023)

[5] A. Hijano, S. Ilić, F. S. Bergeret, "Weak localization at arbitrary disorder in systems with generic spin-dependent fields", arXiv:2311.01148 (2023)

[6] S. Ilić, J. S. Meyer, M. Houzet, "Spectral properties of disordered Ising superconductors with singlet and triplet pairing in in-plane magnetic fields", Phys. Rev. B 108, 214510 (2023)

[7] A. M. Sokolov and T. T. Heikkilä, "Signatures and characterization of dominating Kerr nonlinearity between two driven systems with application to a suspended magnetic beam", Phys. Rev. B 109, 014408 (2024)


← Figure 2. Clamped beam made of magnetic material, where magnetization dynamics and the mechanical vibration are coupled.

# QUANTUM MANY-BODY THEORY

**Professor Robert van Leeuwen**

**The main research focus of the quantum many-body theory group is to develop methods to study interacting quantum many-particle in and out of equilibrium. The main research tools are diagrammatic many-body theory based on nonequilibrium Green's functions and (time-dependent) density-functional theory.** In the recent years there has been an increased attention to the study of systems of coupled electrons and bosons (such as phonons and photons) and several new approaches have been found to establish core theorem that strengthen the foundations of density-functional theory.

*https://www.jyu.fi/en/research-groups/quantum-computing-for-non-equilibrium-many-body-systems*

A major result in 2023 was the publication of a formal mathematical framework, in collaboration with researchers from the University of Rome "Tor Vergata", that allows for for the first time lays the precise foundations of an *ab initio* approach to the electron-phonon problem in real crystals. The work has raised already wide attention in the electronic structure theory community and lead to several invited talk requests and a publication in the prestigious journal Physical Review X [1].

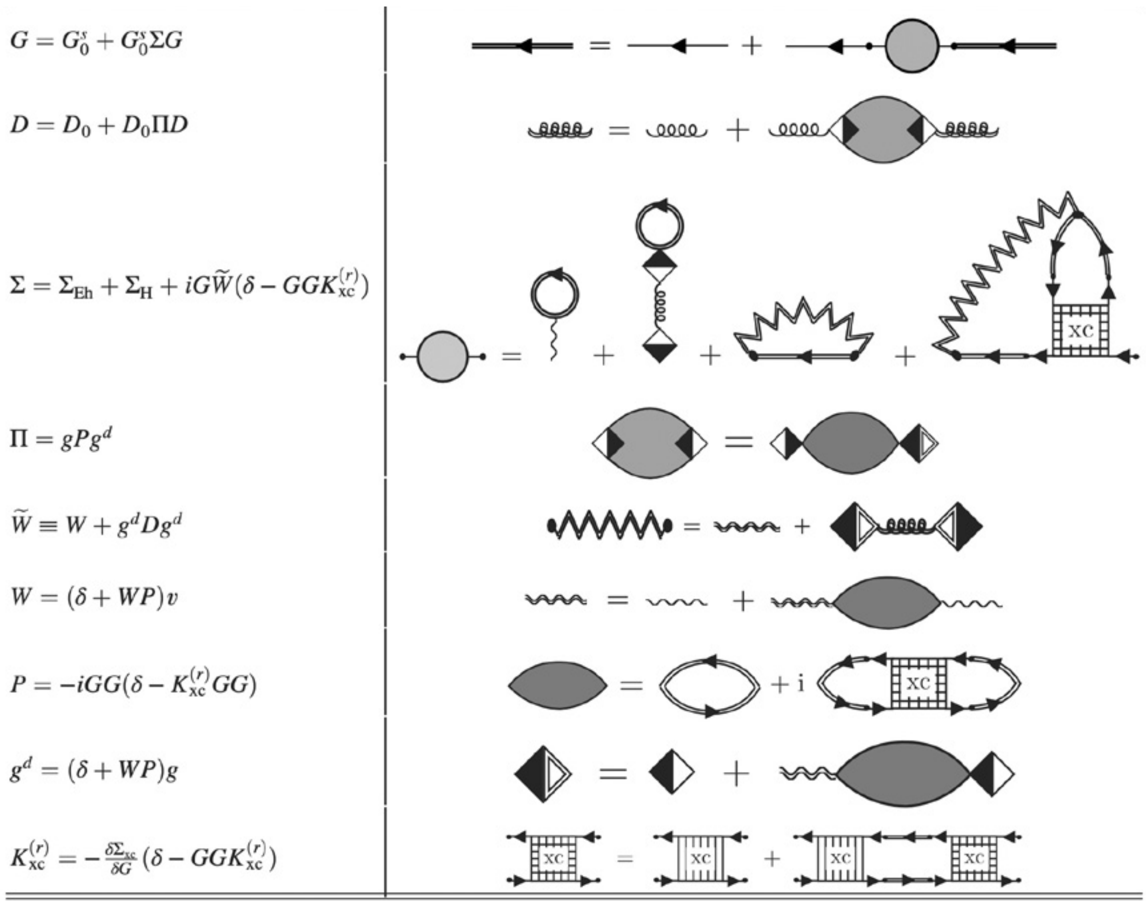
#### IN- AND -OUT OF EQUILIBRIUM AB INITIO THEORY OF ELECTRONS AND PHONONS

In [1] we developed a complete *ab initio* many-body quantum theory of electrons and phonons in equilibrium as well as in steady-state or time-varying settings. The focus was on the harmonic approximation, but the developed tools can readily incorporate anharmonic effects. We demonstrated the necessity of determining the *ab initio* Hamiltonian in a *self-consistent* manner to ensure the existence of an equilibrium state. We then identified the correct partitioning into a "noninteracting" and an "interacting" part to carry out diagrammatic expansions in terms of dressed propagators and screened interactions. The final outcome was the finite-temperature nonequilibrium extension of the Hedin equations, showcasing the emergence of the coupling between electrons and coherent phonons through the time-local Ehrenfest diagram. The Hedin equations have limited practical utility for real-time simulations of systems driven out of equilibrium by external fields. To overcome this limitation, we leveraged the versatility of the diagrammatic approach to generate a closed system of differential equations for the dressed propagators and nuclear displacements (Figure 1). These are the Kadanoff-Baym equations for electrons and phonons. The formalism naturally merges with the theory of conserving approximations, which guarantee the satisfaction of the continuity equation and the conservation of total energy during time evolution. As an example, we show that the popular Born-Oppenheimer approximation is not conserving whereas its dynamical extension is conserving, provided that the electrons are treated in the Fan-Migdal approximation with a dynamically screened electron-phonon coupling. We also derive the formal solution of the Kadanoff-Baym equations for nonequilibrium steady states, which is useful for studies in photovoltaics and optoelectronics. Interestingly, the expansion of the phononic Green's function around the quasiphonon energies points to a correlation-induced splitting of the phonon dispersion in materials with no time-reversal invariance.

**Selected publications**

[1] G. Stefanucci, R. van Leeuwen, and E. Perfetto,
"In and Out-of-Equilibrium Ab Initio Theory of Electrons and Phonons",
Phys.Rev. X13, 031026 (2023)

[2] M. Penz and R. van Leeuwen,
"Geometry of Degeneracy in Potential and Density Space",
Quantum 7, 918 (2023)




↑ Figure 1. The set of diagrammatically derived equations, the so-called Hedin-Baym equations, that fully describe the many-body properties of a real crystal with interaction electrons and phonons.

# 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.

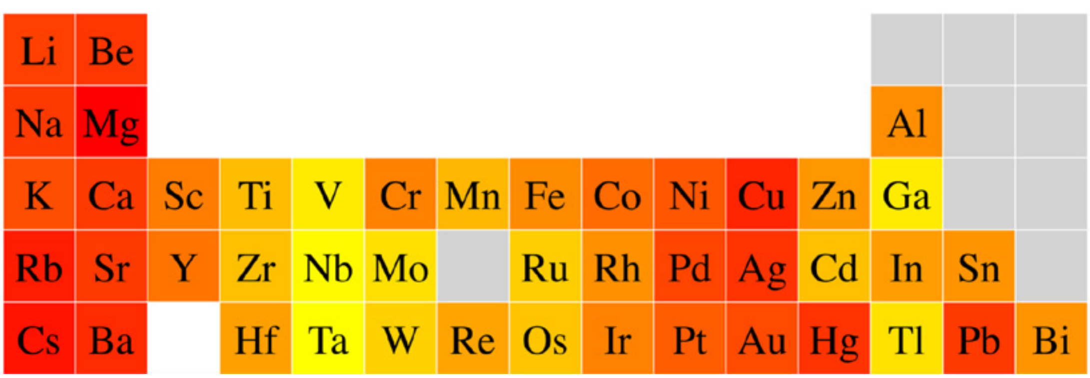
*https://www.jyu.fi/en/research-groups/low-dimensional-nanomaterials-modeling*

#### ATOMICALLY THIN METALLENES BEHAVE LIKE NANOSCALE AMOEBAE

Elemental materials are conventionally characterized by lattice structures and bond lengths that correspond to the minima of their cohesion energy curves. This presumption underlies all research on 3D and 2D materials alike. Even atomically thin metallenes, which lack a layered 2D structure in the bulk form, have been investigated experimentally and theoretically through the lens of this presumption. Yet their stabilization mechanism is extraordinary and relies on nanoscale constrictions, as soap membranes rely on the stabilization by a hoop. This mechanism implies that metallenes can exist under stress at different densities. We have shown that different metallenes can indeed exhibit stable lattices at surprisingly different atomic densities, sometimes excluding the minima of the cohesion energy curves. [1] Consequently, given their softness, ductility, and special stabilization mechanism, the stability of metallenes should be considered using a new concept: they should be considered to have neither well-defined intrinsic structures nor fixed lattice constants but should be regarded as nanoscale amoebae that can adjust to the size and shape of the stabilizing pore. In addition to recognizing promising elements (Figure 1), this novel stability concept enables the creation of new strategies for their experimental realization.

**Selected publications**

[1.] *Strain-stabilized atomically thin metallenes*, Kameyab Raza Abidi and Pekka Koskinen (under review)




↑ Figure 1. Based on density-functional simulations, we propose a new paradigm for assessing the stability of 45 two-dimensional metals and rank them accordingly (red elements are more stable).

# ACCELERATOR LABORATORY

**Professor Paul Greenlees**
**Head of Accelerator Laboratory**

**As in 2022, 2023 represented another anniversary in the history of accelerator-based science in Jyväskylä.** The first MC-20 cyclotron was delivered to the Department of Physics in December 1973, thus 2023 marked *50 years* of accelerators driving scientific discoveries in the University. As usual, 2023 was a busy year for the Accelerator Laboratory, with some high-profile scientific results and our researchers attracting worldwide visibility. Research from the laboratory also resulted in the publication of a large number of PhD theses, a total of nine being defended during the year. Two particular highlights from 2023 were the first direct mass measurement of the high-spin isomeric state in $^{94}$Ag and the observation of a new isotope of the very rare element astatine, namely $^{190}$At. The properties of the nucleus $^{94}$Ag are such that this nucleus features in the strategic plans of almost all large-scale accelerator facilities around the world. Being the first to determine the masses of the exotic excited states in this nucleus is a real feather in the cap of the Exotic Nuclei and Beams group. The Accelerator Laboratory has a long history of producing new isotopes, but few cases have garnered as much attention as one of our most recently published results, that of $^{190}$At. The discovery of the new isotope formed the basis of the M.Sc. thesis and related publication of Henna Kokkonen, under the supervision of Kalle Auranen. The work, and Henna, received worldwide attention and many accolades, culminating in an invitation from the President to the Independence Day celebrations at the Presidential Palace and television interviews. Henna is to be congratulated for her poise during her time in the spotlight.

**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 2023, the K130 cyclotron delivered 6077 hours of beam to experiments, with the average per year from 1996 onwards being 6408 hours. A total of more than 50 different "runs" were carried out, mainly distributed between Nuclear Spectroscopy (36%), RADEF and industrial applications (28%) and IGISOL (32%). As in 2022, more time was dedicated to pre-emptive maintenance of the accelerator infrastructure, in particular the K130 cyclotron. A total of around six weeks were dedicated to maintenance, with several weeks scheduled in January when it is expected that the demand and cost of electricity is at its highest. The technical team, ably led by Taneli Kalvas and Risto Kronholm, made significant progress in the eternal struggle to bring the K30 (MCC30/15) cyclotron into reliable operation. Improvements to the control and interlock systems, innumerable technical fixes to bring parts to the correct specifications and much deeper understanding of the operation of the RF system led to the possibility to test long-term stability of the RF system at the correct operating point. Mikko Rossi implemented new control software and it was possible to demonstrate acceleration of protons to low energies after injection into the cyclotron. Following these successful tests, efforts have been made to finalise the repairs to the ion source and services in the cyclotron bunker, before testing with full acceleration of the beam which will result in increased radiation levels. The next tests will be carried out in 2024.

**The year also saw some important applications submitted and continuations of existing contracts.** As part of the University negotiations with the Ministry of Education and Culture, a new bid was submitted to justify the continuation of the National Task designated to the Accelerator Laboratory. The Accelerator Laboratory has a National Task to provide high-level research and education in the use of radiation and accelerator-based science. These themes remain extremely important in Finland, due to the large reliance on nuclear energy and also through research into radiation safety, security and safeguards. The latter research has largely been removed from the portfolio of STUK and transferred to the Universities. The long-term collaboration with the European Space Agency was again formalised in the form of a new contract, realised through the hard work and dedication of Heikki Kettunen. Such long-term collaboration and continuation of contracts is very important to maintain the stability of funding at the Accelerator Laboratory. Further good news came from the Academy of Finland, with an Academy Researcher position being awarded to Zhuang Ge and an Academy Project grant to Anu Kankainen.

**Another important milestone in the year was the delivery of a full ToF-ERDA beamline to the Advanced Technologies Research Institute of the Slovak University of Technology (Trnava, Slovakia)**. The delivery represented the second such commercial order for a beamline based on technologies developed by the Accelerator-Based Materials Research group, following the one delivered to the University of Surrey, UK, in the previous year. The delivery of such devices not only expands our research collaboration network but also provides useful income for the Department of Physics.

**As part of the Ylistö Campus renovation project, it had been envisaged, and indeed the planning was at a very advanced stage, for the Accelerator Laboratory target hall to be extended in order to house the new 3MV accelerator platform**. The 3MV accelerator project received a positive funding decision from the Academy of Finland in 2022 and the procurement procedure was due to start. The 3MV platform will bring a new capability to deliver neutron beams for the user community. Unfortunately, despite the extensive work that had been carried out in the planning phase, it was finally decided that the costs to realise the extension and subsequent rent increase were beyond the expected level of future resources available. Thus, it is now necessary to house the 3MV platform within the existing floor space of the laboratory. The change in plans will mean a significant amount of planning and reconstruction work for the staff of the laboratory, and potentially some disruption to the facility operations. It is currently expected that the planning work will be done in 2024 and the reconstruction of the target hall in 2025.

**Aside from those mentioned above, a number of our researchers were recognised for their work throughout the year**. Anu Kankainen was awarded the Väisälä prize 2023 for her work on precision atomic mass measurements for nuclear astrophysics and elected as a member of the Finnish Academy of Science and Letters. Janne Pakarinen was awarded was awarded the Tomek Czosnyka Honorary Award for opening new avenues in Coulomb-excitation studies by the University of Warsaw, Poland. Marjut Hukkanen was awarded the Hannu Koskinen prize for the best oral presentation at the Annual Finnish Physics Days in Tampere. Sonja Kujanpää received the best poster presentation prize at the Mazurian Lakes Conference.

**The year also saw some changes in the permanent staff of the laboratory, with a number of faces who have been almost ever-present in the history of the laboratory leaving us**. Cyclotron operator Anssi Ikonen left his position to pursue his own business interests and was replaced by Esa Hyyryläinen. There were also two significant retirements – Chief Engineer Pauli Heikkinen and University Researcher Wladek Trzaska. Pauli began his career in 1982 and in the late eighties was responsible for the design of the "35-metre" version of the CRYRING storage ring. Pauli played an important role in the design of the K130 cyclotron, which has been the backbone of the Accelerator Laboratory operations for over 30 years. A great deal of tacit knowledge leaves with Pauli. Wladek joined the Department in 1980, in the group of Juhani Kantele. Wladek has had an exceptionally broad and varied career, with particular focus on developing new instrumentation and methods for nuclear, particle and astroparticle physics. Wladek led the work of the HENDES group on nuclear reactions and fission studies, and in more recent years has played a leading role in the ALICE collaboration, developing the FIT system which plays key role in the operation the ALICE experiment. Wladek has also been active in the DUNE and JUNO collaborations and in underground physics experiments at the Pyhäsalmi mine. We wish both Pauli and Wladek all the best for their retirements, with Wladek continuing in the Department with Emeritus status.

**Once again, I would like to thank all the staff of the Accelerator Laboratory for their exceptional dedication and hard work, without whom none of our achievements would be possible**. It always makes me very proud to go out into the international community and hear how well our efforts are appreciated and recognised worldwide.

# NUCLEAR SPECTROSCOPY

**Senior Researcher Janne Pakarinen,**
**Academy Research Fellow Kalle Auranen,**
**Post-doctoral Researcher Andrew Briscoe**

**The Nuclear Spectroscopy group investigates the structure of rare atomic nuclei mainly produced via fusion-evaporation reactions.** We perform experiments at the RITU and MARA recoil separators combined with various ancillary detection systems, such as the JUROGAM 3 γ-ray spectrometer, the APPA plunger device, the JYTube charge-particle veto detector and the SAGE spectrometer. These studies are mainly focused on proton-rich and very heavy nuclei. We are also actively involved in international collaborations such as Miniball and the ISOLDE Decay Station at ISOLDE, CERN, in the AGATA collaboration to build a γ-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 year 2023 was filled with experiments utilizing the entire arsenal of instruments at our disposal. We demonstrated several swift changes of measurement set-ups, not only between the MARA and RITU separators, but also from in-beam to focal-plane experiments, in short succession. In total, we performed 13 measurements, summing up to a total of 101 days of beam on target. For the first time, the APPA plunger device was installed at RITU and ran successfully in challenging conditions due to vibrations arising from the differential pumping system. The APPA campaign at RITU, performed with the stripped-down version of the JUROGAM 3 array of 15 Phase1 detectors in backward angles, focused on lifetime measurements of very heavy nuclei $^{167}$Os, $^{190}$Pb and $^{192}$Po. After four focal-plane experiments, three at MARA and one at RITU, the GAMMAPOOL Clover detectors returned from Orsay, France in September. The second campaign with the full JUROGAM 3 array started in October at MARA. In conjunction with the APPA and JYTube ancillary devices, we investigated the physics of nuclei close to the N=Z line. We also commissioned a new liquid-nitrogen autofill system which was developed in-house. It has proven not only to offer improved and smooth operation, but has also remarkably lowered the liquid nitrogen consumption.

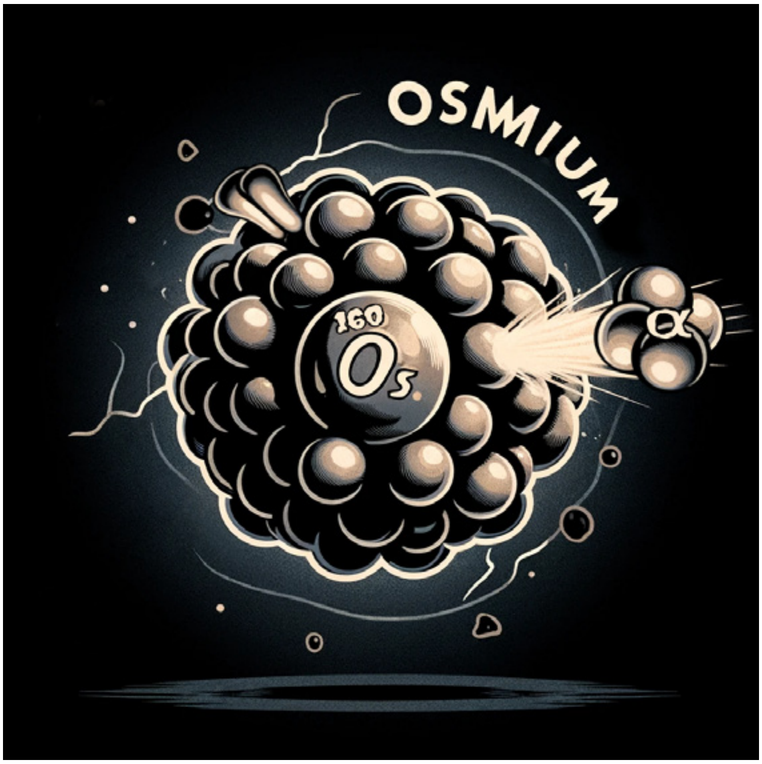
Four group members successfully defended their Doctoral theses. In *"Combined γ-ray and Electron Spectroscopy: Study of Shape Coexistence in $^{186}$Pb"*, Joonas Ojala reassigned the shapes of the band-head $0^+$ states. George Zimba's work shed light on *"Spectroscopy along the N = Z line between mass 70 and 84"* and Minna Luoma presented FAIR-related work on *"New β-decay half-lives of heavy neutron-rich nuclei and performance studies of the GEM-TPC detector"*. Holly Tann, a dual-doctorate researcher in the program between the University of Jyväskylä and the University of Liverpool, UK, studied *"Excited States in the Highly Deformed Proton Emitter $^{131}$Eu"*. In her MSc thesis, Henna Kokkonen reported on the discovery of the new atomic nucleus $^{190}$At. The work attracted significant attention, and provided Henna with several accolades, such as the *"Scientific Breakthrough Award"* from the University of Jyväskylä, *"Science communicator of the year"* from the Physics Club, an invitation to annual Independence Day celebration in the Presidential Palace, and broad national and international visibility. Henna also continued as a doctoral researcher in our group, while Jamie Chadderdon and Adam McCarter from the University of Liverpool joined us on Long-Term Attachments. Janne Pakarinen was awarded the Tomek Czosnyka Honorary Award *"for opening new avenues in Coulomb-excitation studies by performing, for the first time, electron spectroscopy of Coulomb excited states following the development of the SPEDE spectrometer"* by the University of Warsaw, Poland.

↑ Figure 1. The Nuclear Spectroscopy group enjoying a sunny day in Ladun Maja in Spring 2023.

### DISCOVERY OF NEW ISOTOPES $^{160}$OS, $^{156}$W, AND $^{190}$AT

A new atomic nucleus $^{160}$Os (Figure 2), comprised of 76 protons and 84 neutrons, has been synthesized with fusion-evaporation reactions to allow the study of its decay properties for the first time. A 310 MeV beam of $^{58}$Ni ions was incident upon on an enriched $^{106}$Cd target which enabled the neutron evaporation channels from the $^{164}$Os compound nucleus to be isolated with the aid of the JYTube device and the MARA separator. Alpha decays were observed from the $8^+$ and $0^+$ levels in $^{160}$Os, which is expected to be the lightest alpha-emitting isotope of Os due to its proximity to the N=82 shell closure. Theoretical models predict $^{160}$Os to be unbound to 2p emission by ≈2.5 MeV, too low to observe, yet competition from this decay mode could be expected in lighter isotopes. The β-decay properties of its daughter, $^{156}$W, were also studied for first time and feeding of both the $(2^-)$ ground state and $(9^+)$ isomeric state was observed, in contrast with its lighter isotones where exclusive feeding of the low-spin states has been previously established.

↓ Figure 2. AI inspired visualization of the $^{160}$Os nucleus emitting an alpha-particle.



As mentioned above,we have also succeeded in producing a previously unknown atomic nucleus, $^{190}$At, consisting of 85 protons and 105 neutrons. The nucleus is the lightest isotope of astatine discovered to date. Astatine is a short-lived, and therefore rare element. It has been estimated that in the Earth's crust there is no more than one tablespoon of astatine. The new isotope was produced in the fusion of $^{84}$Sr beam particles and silver target atoms, and it was detected among the reaction products by using the focal-plane detectors of the RITU recoil separator. $^{190}$At was found to decay towards more stable isotopes via unhindered α decay, hence, it was concluded that the α particle is most likely emitted from a high-spin ($10^-$) state. Another decay mode, proton emission, was found to be energetically allowed from $^{190}$At, but it was found to be unable to compete with the α-decay process.

These results aid the development of our understanding of how exotic highly proton-rich nuclei decay in unexplored regions of the nuclear chart and to our knowledge of the limits of nuclear existence.

### EXAMINING COMPETING SHAPES AND THE ONSET OF DEFORMATION IN $^{190}$PB

Over the years, the neutron-deficient Pb isotopes have provided grounds for extensive experimental and theoretical studies of competing and coexisting nucleon configurations. Close to the N=104 midshell, structures associated with different shapes appear close to the spherical ground state. In order to understand these interesting phenomena, complementary experimental techniques are needed. For the first time, we have measured the lifetimes of states belonging to two different bands in a Pb isotope, namely $^{190}$Pb, as shown in Figure 3. These data, in combination with earlier simultaneous in-beam gamma-ray and electron spectroscopic data, have provided us with unprecedented insight into the structure of this exotic nucleus.

### Selected publications

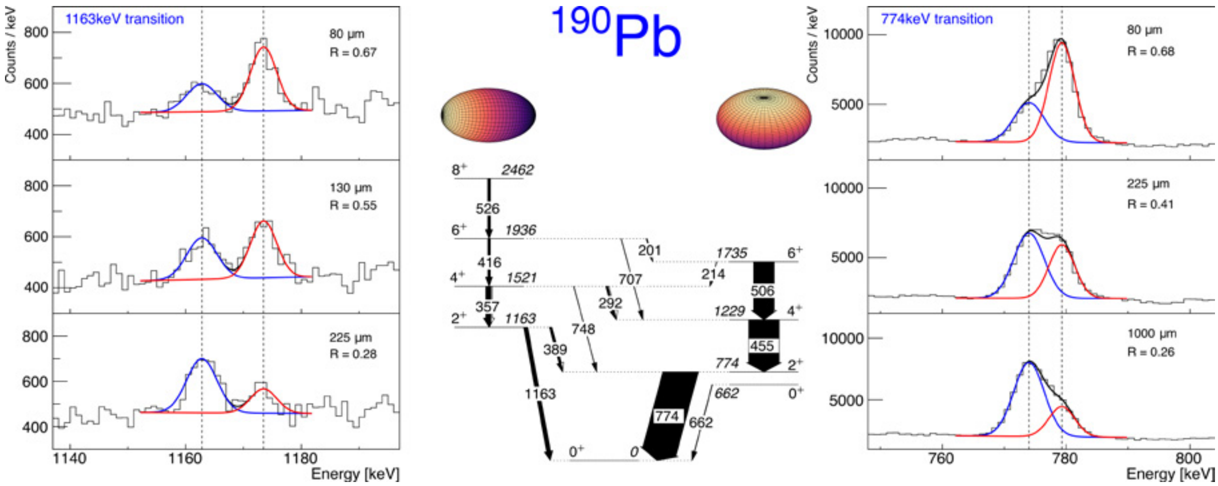

Properties of the new α-decaying isotope $^{190}$At
Kokkonen, H., Auranen, K., Uusitalo, J., Eeckhaudt, S., Grahn, T., Greenlees, P. T., Jones, P., Julin, R., Juutinen, S., Leino, M., Leppänen, A.-P., Nyman, M., Pakarinen, J., Rahkila, P., Sarén, J., Scholey, C., Sorri, J., & Venhart, M.
Physical Review C, 107, 064312 (2023)
*https://doi.org/10.1103/PhysRevC.107.064312*

Decay spectroscopy at the two-proton drip line:
Radioactivity of the new nuclides $^{160}$Os and $^{156}$W
Briscoe, A.D., Page, R.D., Uusitalo, J., Joss, D.T., AlAqeel, M.A.M., Alayed, B., Andel, B., Antalic, S., Auranen, K., Ayatollahzadeh, H., Badran, H., Barber, L., Beeton, G., Birova, M., Bogdanoff, V., Clark, R. M., Cubiss, J. G., Cullen, D. M., Deary, J., . . . Zimba, G.
Physics Letters B, 847, 138310 (2023)
*https://doi.org/10.1016/j.physletb.2023.138310*

The spectroscopic quadrupole moment of the $2_1^+$ state of $^{12}$C :
A benchmark of theoretical models
Saiz-Lomas, J., Petri, M., Lee, I. Y., Syndikus, I., Heil, S., Allmond, J. M., Gaffney, L. P., Pakarinen, J., Badran, H., Calverley, T., Cox, D. M., Forsberg, U., Grahn, T., Greenlees, P., Hadyńska-Klęk, K., Hilton, J., Jenkinson, M., Julin, R., Konki, J., . . . Wadsworth, R.
Physics Letters B, 845, 138114 (2023)
*https://doi.org/10.1016/j.physletb.2023.138114*

Isospin symmetry in the T = 1, A = 62 triplet
Wimmer, K., Ruotsalainen, P., Lenzi, S.M., Poves, A., Hüyük, T., Browne, F., Doornenbal, P., Koiwai, T., Arici, T., Auranen, K., Bentley, M.A., Cortés, M.L., Delafosse, C., Eronen, T., Ge, Z., Grahn, T., Greenlees, P.T., Illana, A., Imai, N., . . . Yajzey, R.
Physics Letters B, 847, 138249 (2023)
*https://doi.org/10.1016/j.physletb.2023.138249*


↓ Figure 3. Examples of gamma-ray energy shifts corresponding to three different target-degrader distances obtained for transitions from the yrast (right) and non-yrast (left) $2^+$ states in $^{190}$Pb. The predominant shapes of these states and bands feeding them are tentatively illustrated above the partial level scheme in the middle.



# EXOTIC NUCLEI AND BEAMS

**Professors Ari Jokinen,**
**Anu Kankainen and Iain Moore**
**Staff Scientist Mikael Reponen**
**Senior researcher Tommi Eronen**

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

*https://www.jyu.fi/igisol*

#### ON-GOING RESEARCH PROJECTS AND PERSONNEL NEWS

Our group continues to benefit from a variety of external funding sources. The Research Council of Finland project PANTHER continues in a consortium led by Iain Moore and theorist Markus Kortelainen, focused on advancing our understanding of the actinide elements. 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. We are a beneficiary in the Marie Curie Innovative Training Network, LISA (Laser Ionization and Spectroscopy of Actinides).

Zhuang Ge started as an academy research fellow in the group in September 2023. His project "Mass measurements of exotic N=Z nuclei (up to Sn-100) and the vicinity for nuclear physics and nuclear astrophysics studies" will utilize the MR-TOF and JYFLTRAP Penning trap for high-precision mass measurements at IGISOL.

A new Research Council of Finland project led by Anu Kankainen, "Heavy Exotic Nuclei for Nuclear Astrophysics (HENNA)" was also started in September 2023. The project will continue the studies of neutron-rich nuclei started in the ERC CoG project MAIDEN, which finished in November 2023.

Three cotutelle-PhD theses were defended in the group in 2023. Lama Al Ayoubi's PhD thesis *"Nuclear structure at the neutron emission threshold and below explored via beta-decays of* $^{82,83}$*Ga and* $^{86}$*As"*, was done in cotutelle with Université Paris Saclay; Marjut Hukkanen's PhD thesis, *"Penning-trap mass spectrometry: commissioning of PIPERADE and measurements of neutron-rich A = 100–120 nuclei at JYFLTRAP"* in cotutelle with University of Bordeaux, and Alejandro Ortiz Cortes's thesis *"Palladium: a Study of Nuclear Deformation of a Refractory Element"* with University of Caen Normandy.

The research in the group was also acknowledged with personal awards in 2023. Marjut Hukkanen was awarded Hannu Koskinen's prize for the best oral presentation at the Annual Finnish Physics Days in Tampere. Sonja Kujanpää received the best poster presentation prize at the Mazurian Lakes Conference. Anu Kankainen was awarded the Väisälä prize 2023 and elected as a member of the Finnish Academy of Science and Letters. In other news, we hosted a JSPS Alumni Seminar, discussing collaborative activities between ACCLAB and KEK-WNSC in Japan. Funding for this event was obtained by Mikael Reponen.

#### TECHNICAL DEVELOPMENTS

In 2023, developments continued both with MORA (Matter's Origin from RadioActivity experiment), RAPTOR (the new collinear resonance ionization spectroscopy beamline), as well as the atom trap station. Our actinide activities also progressed, with a new large volume gas cell designed to host multiple Pu-239 alpha-recoil sources used for producing a beam of U-235m. With the addition of electric field guidance, several thousands of U ions per second were detected, in the doubly- and triply charged states. Ongoing work proceeds to find a way to manipulate the charge states to preferentially populate the singly charged ion, suitable for collinear laser spectroscopy. Our collaboration with CEA Saclay for nuclear decay spectroscopy of actinide isotopes also continued, with a visit from CEA engineers to measure the available space for SEASON (Spectroscopy Electron Alpha in Silicon bOx couNter), which will be commissioned at IGISOL in late 2024, before moving to S3 at GANIL.

Our contributions to FAIR include the ongoing development and construction of a new ion beam cooler-buncher for the NUSTAR collaborations MATS and LaSpec. This device, named HIBISCUS, is in the final stages of construction on the roof of IGISOL. The work is led by PhD student Arthur Jaries.

## RESEARCH HIGHLIGHTS

Here we summarize selected experimental and publication highlights from 2023.

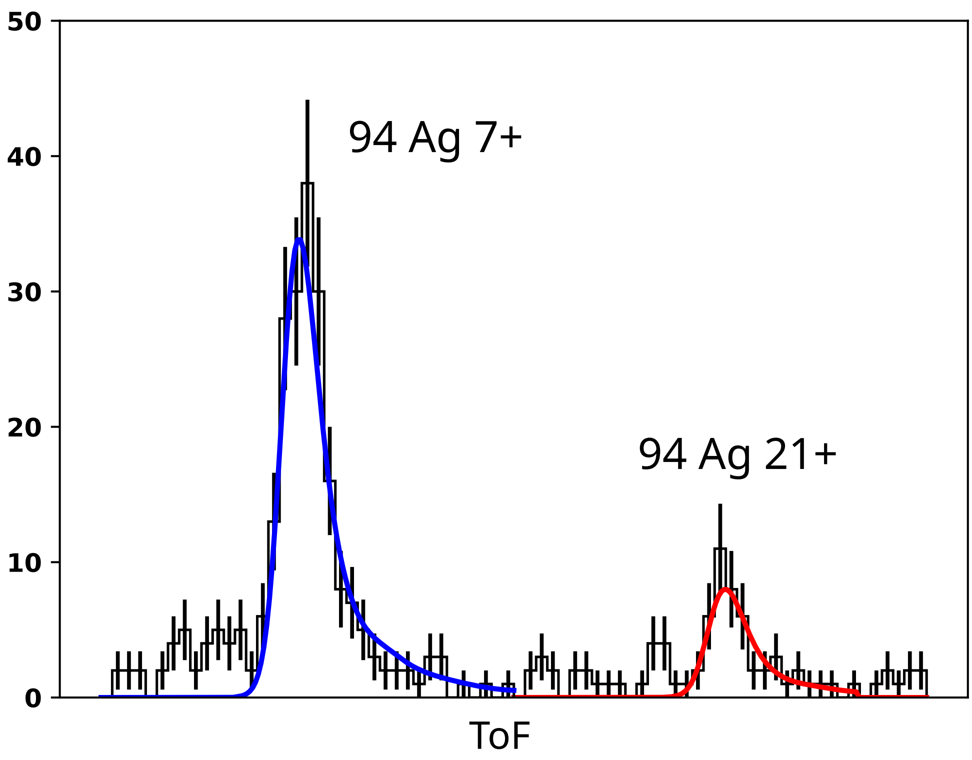
### First direct mass measurement of the 21+ isomer in silver-94

The *N*=*Z* region of the chart of nuclei hosts several nuclei with interesting properties. A particularly prominent case is the isotope Ag-94, which exhibits one of the most unique isomers in existence. In addition to a low-spin 7+ β-delayed proton-decaying isomer, Ag-94 has been identified as having a spin-trap isomer with the highest spin, 21+ ever observed for β -decaying nuclei. The isomer's long half-life, high excitation energy and high spin are matched by an unparalleled selection of decay modes including, among others, β -decay and one-proton decay. However, the claimed existence [1] of the most exotic mode of decay mode, namely a two-proton emission, has been a matter of intense discussion for nearly two decades. To resolve this, a direct mass measurement of the 21+ isomer was performed at IGISOL in May 2023 using recently developed efficient production [2] and multi-reflection time-of-flight mass measurement techniques, bringing this long-standing question on the cusp of being resolved (Figure 1).

[1] Mukha, I. *et al.* Proton–proton correlations observed in two-proton radioactivity of 94Ag. Nature 439, 298–302 (2006)

[2] Reponen, M. *et al.* Evidence of a sudden increase in the nuclear size of proton rich silver-96. Nature Communications 12, 4596 (2021)

↓ Figure 1. Time-of-flight spectrum for Ag-94, measured with the MR-TOF at IGISOL.

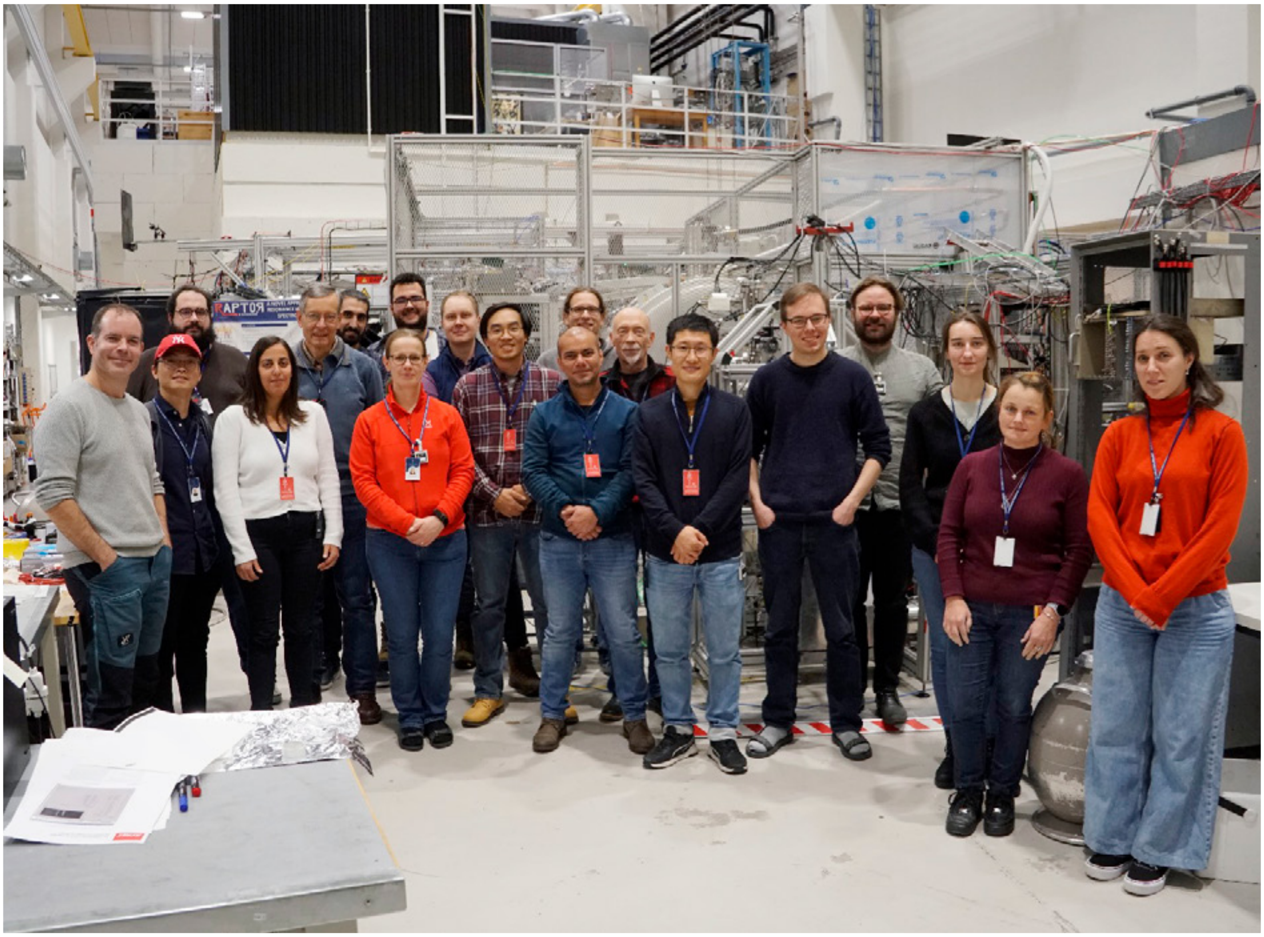


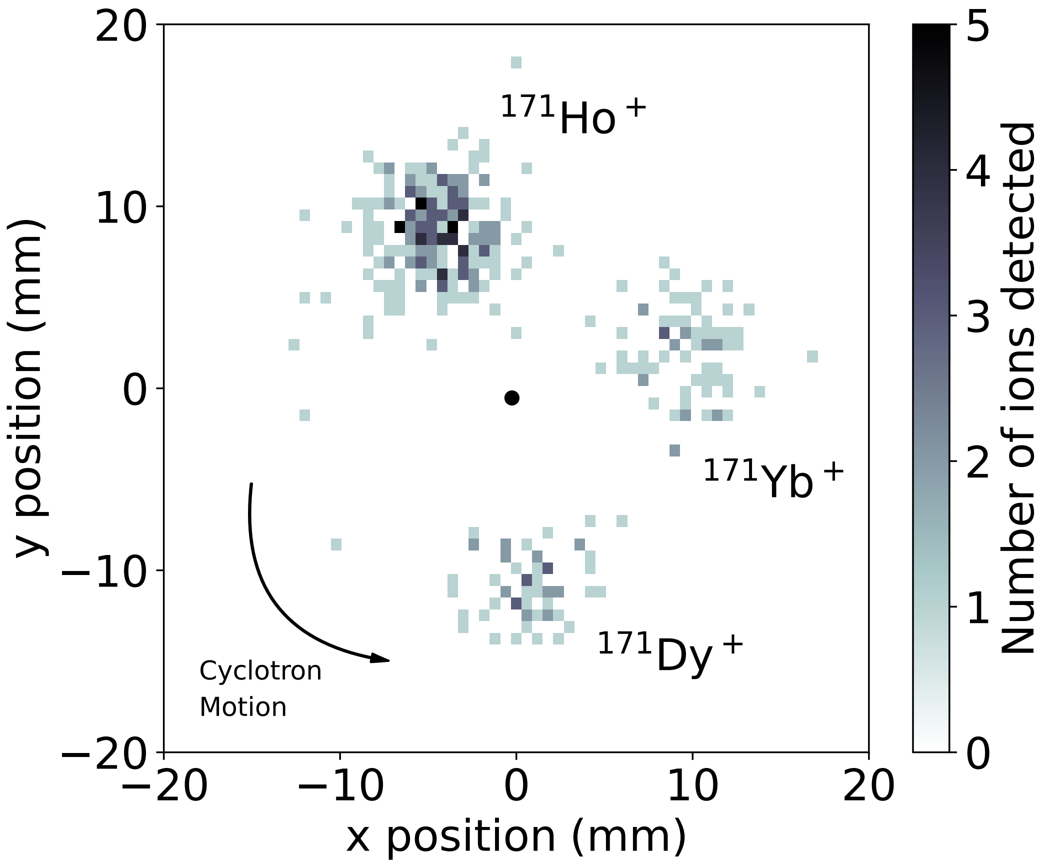
**Studying Am isotopes for the first time at IGISOL**

With support from the Super-FRS experiment collaboration, FAIR, we successfully extracted beams of americium for the first time at IGISOL (Figure 2), using a reaction of deuterons on "drop-on-demand" targets of Pu-242. The goal was to populate both ground states and fission isomers in Am-240,242. By operating IGISOL in a duty-cycle mode, we could either deliver radioactive beams to a silicon detector setup in the switchyard of the mass separator, or to the RF cooler for subsequent transport towards the MR-TOF mass spectrometer or JYFLTRAP. JYFLTRAP was used to separate Am-242 from target ions of Pu-242.

Several beam energies allowed for an investigation of the excitation function to benchmark Talys simulations. Half-lives and the total kinetic energy of the fission fragments from Am-240f,242f were measured. The excitation energy of Am-242f was explored with the MR-TOF. These exciting developments provide impetus for further online actinide studies in the future.

↓ Figure 2. Happy investigators from the Super-FRS experiment collaboration, with local participants for a successful americium experiment.






↑ Figure 3. Dy-171 and Ho-171 measured at JYFLTRAP with the PI-ICR technique. These are the heaviest fission fragments from U-238(p,f) measured with JYFLTRAP. Stable Yb-171 ions are also indicated.

**Extending the mass measurements in the neutron-rich rare-earth region to heavier and more exotic nuclei**

Altogether, masses of 19 neutron-rich rare-earth isotopes were measured with JYFLTRAP during a very successful beamtime in 2023. The measurements provided the first experimentally determined mass values for 5 nuclides. With the phase-imaging ion cyclotron resonance technique, the precision of the previously known nuclides could be significantly improved, and the measurements were extended to the heaviest fission fragments measured at IGISOL so far (see Fig. 3). The masses have a strong impact on the astrophysical rapid neutron capture process and its produced heavy-element abundances. In addition, the evolution of nuclear structure around the $Z$~64, $N$~104 midshell region can be probed via these precision mass measurements.

**Selected publication highlights from 2023**


[1] L.G. Sarmiento *et al.*, "Elucidating the nature of the proton radioactivity and branching ratio on the first proton emitter discovered 53mCo". Nat Commun 14, 5961 (2023).
*https://doi.org/10.1038/s41467-023-39389-2*

[2] L. Nies, L. Canete *et al.*, "Further Evidence for Shape Coexistence in $^{79}$Zn$^m$ near Doubly Magic 78Ni", Phys. Rev. Lett. 131, 222503 (2023).
*https://doi.org/10.1103/PhysRevLett.131.222503*

[3] P. Plattner *et al.*, "Nuclear Charge Radius of 26mAl and Its Implication for Vud in the Quark Mixing Matrix", Phys. Rev. Lett. 131, 222502 (2023).
*https://doi.org/10.1103/PhysRevLett.131.222502*

[4] A. Koszorus *et al.*, "High-precision measurements of the hyperfine structure of cobalt ions in the deep ultraviolet range", Scientific Reports, 13(1), 4783 (2023).
*https://doi.org/10.1038/s41598-023-31378-1*

[5] M. Hukkanen *et al.*, "Odd-odd neutron-rich rhodium isotopes studied with the double Penning trap JYFLTRAP", Phys. Rev. C 107, 014306 (2023).
*https://doi.org/10.1103/PhysRevC.107.014306*

# 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, HENDES contributes to the design, construction, and upgrade of ALICE at CERN, JUNO and DUNE neutrino experiments, NEMESIS indirect Dark Matter searches, and other underground physics experiments.

It is the final HENDES contribution to the JYFL Annual Reports. At the end of June 2023, after four decades at the JyU Physics Department, including three decades at the Accelerator Laboratory, I have reached the obligatory retirement age and continue as an Emeritus. At the same time, the HENDES detector laboratory at JYFL is closing, and the Large Scattering Chamber cavern in the cyclotron target hall will be cleared to accommodate the new tandem accelerator.

Developing new instruments and methods for nuclear, particle, and astroparticle physics was not only a great adventure but also guaranteed a steady flow of peer-reviewed publications (Fig. 1). This growing trend should continue well into the next decade as the JUNO data-taking period starts already in 2025, the first DUNE results are expected in 2028, and the FIT detector will serve ALICE until the end of the LHC Run 4 in 2032.

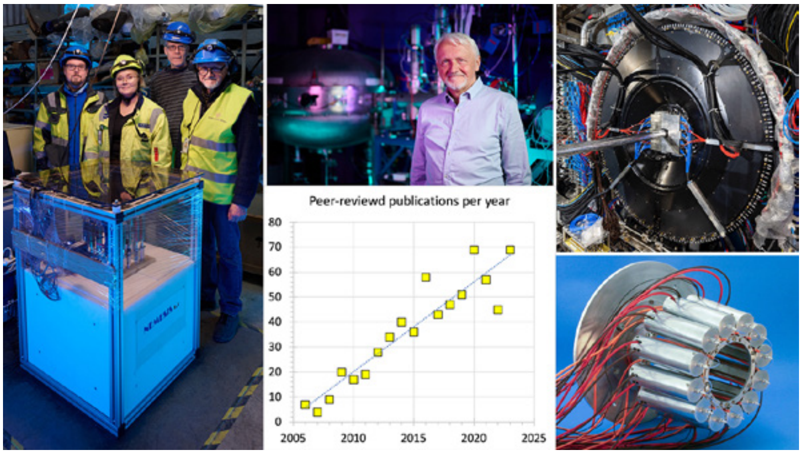
**Selected publications**

[1] Lhersonneau, G., Jones, P., Fadil, M., Malkiewicz, T., & Trzaska, W. H. (2023). Experimental cross sections in fission of natural uranium induced by a neutron spectrum of 12.4-MeV average energy. European Physical Journal Plus, 138(3), Article 303. *https://doi.org/10.1140/epjp/s13360-023-03912-7*

[2] J.M. Mejía Camacho et al. Forward Diffractive Detector control system for Run 3 in the ALICE experiment. Nuclear Inst. and Methods in Physics Research, A1050(2023) 168146. *https://doi.org/10.1016/j.nima.2023.168146*

[3] T. Anderson et al. (2023). Eos: conceptual design for a demonstrator of hybrid optical detector technology. Journal of Instrumentation, 18(2), Article P02009. *https://doi.org/10.1088/1748-0221/18/02/P02009*

[4] W.H. Trzaska et al. New Evidence for DM-like Anomalies in Neutron Multiplicity Spectra. PoS (TAUP2023) 083. *https://doi.org/10.22323/1.441.0083*




← Figure 1. Centre – HENDES peer-reviewed publications per year over the past two decades. Clockwise from the left: NEMESIS 1.4 experiment, Large Scattering Chamber at JYFL, ALICE FIT detector (LHC Run 3 and 4), and ALICE T0 detector (LHC Run 1 and 2).

↑ No FIT, no ALICE

# NUCLEAR STRUCTURE AND NUCLEAR PROCESSES

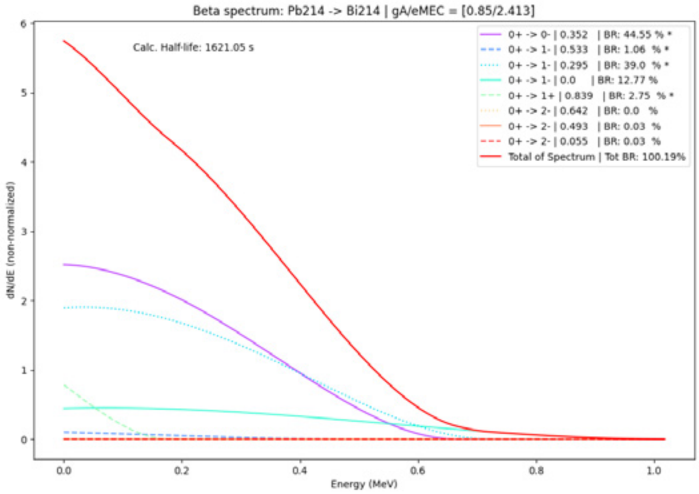
**Professor Jouni Suhonen**

**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 JYFLTRAP group, as well as some external theory partners.

## BETA DECAYS AS BACKGROUNDS IN RARE-EVENTS EXPERIMENTS

Searches for beyond-the-standard-model (BSM) physics typically involve rare-events experiments measuring, e.g., single and double beta decays related to the neutrino properties, neutrino-nucleus scatterings related to properties of the sun and supernovae and WIMP-nucleus (Weakly Interacting Massive Particle) scatterings related to the quest for the cold dark matter of the Universe. Experimental and theoretical studies of single beta decays are important in the context of resolving the anomalies related to the antineutrino flux from nuclear reactors [1], when looking for the effective value of the weak axial coupling [2] and in assessing the common backgrounds in the rare-events experiments themselves [3]. Measurements of beta decays of very low decay energies (Q values) are also important for direct determination of the (anti)neutrino mass [4].

Common backgrounds in the BSM-related experiments are the beta-electron spectra of radioactive nuclei in the 220-Rn and 222-Rn radioactive chains, radon being a common background in the underground facilities. The radon background causes the following beta-decay chains 212-Pb --> 212-Bi --> 212-Po and 214-Pb --> 214-Bi --> 214-Po which are backgrounds, e.g., in dark-matter experiments like XENON1T, XENONnT, PandaX, etc. In [3] these decays were discussed in detail by also computing their total beta-electron spectra. These total spectra involve large numbers of individual transitions, the spectral shapes of which are sensitive to the nuclear structure through the nuclear wave functions of the initial and final state. An example of such a collection of individual beta transitions, the total spectrum corresponding to the beta decay of 214-Pb is depicted in figure 1.




↑ Figure 1. Beta spectral shapes of individual transitions from the 0+ ground state of 214-Pb to 0-, 1- (first-forbidden non-unique transitions), 2- first-forbidden unique transitions) and a 1+ (allowed transition) states in 214-Bi. The thick red line represents the total summed spectral shape.

**THE NEPTUN PROJECT**


In 2023 a project named NEPTUN (NEutrino Properties Through Use of Nuclei) got some 1.4 MEURO from the EU for 3 years. The project started at the beginning of July 2023 and the funding goes through the Romanian Ministry of Research, Innovation and Digitization (PNRR-I8/C9-CF264, Contract No. 760100/23.05.2023) and the host institute CIFRA ("Centre International de Formation et de Recherche Avancees en physique"), with the English name: "International Centre for Advanced Training and Research in Physics". NEPTUN was one of the highest-ranked projects in a competition to be included in Romania's National Recovery and Resilience Plan under pillar I8: "Development of a program to attract highly specialized human resources from abroad in research, development and innovation activities".

The host institute CIFRA (*https://cifra-c2unesco.ro*) was established under the agreement between the Romanian government and UNESCO, ratified in 2013. CIFRA officially started its activity on February 9, 2017, when the agreement with UNESCO entered into force, and is coordinated by the Division of Science Policy and Capacity Building, UNESCO Natural Sciences sector.

As the name of the project indicates, NEPTUN concentrates on development of new theoretical methods and advanced computational programs for the investigation of the properties of neutrinos produced in various weak-interaction processes. In particular, the project aims to significantly contribute to i) determination of the effective value of the weak axial coupling, ii) studies of the existence of sterile neutrinos, iii) complementary approaches to help improve the precision of the nuclear matrix elements related to the neutrinoless double beta decay, and iv) derive (anti)neutrino masses from beta and double beta decays. All these topics are hot issues in contemporary nuclear and particle physics.

The team structure of NEPTUN is as follows: Prof. Jouni Suhonen (Jyväskylä and CIFRA), Research Director, (1st year 25% and last two years, after retirement, 100% employment), Prof. Sabin Stoica (CIFRA), project manager (50% employment), Prof. Mihai Horoi (Central Michigan University), senior researcher (20% employment), Dr. Andrei Neacsu (CIFRA), senior researcher (50% employment), and Dr. Jenni Kotila (Jyväskylä), senior researcher (20% employment). The rest of the money goes to hiring PhD students and postdocs.

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

[2] M. Ramalho and J. Suhonen, Physical Review C 109, 034321 (2024).

[3] M. Ramalho and J. Suhonen, Physical Review C 109, 014326 (2024).

[4] M. Ramalho et al., Physical Review C 106, 015501 (2022).

# GLOBAL PROPERTIES OF NUCLEI

**Associate professor Markus Kortelainen**

**Our group develops and applies nuclear structure models, focusing mainly on the nuclear density functional theory (DFT) as a theoretical framework**. Our goal is to improve nuclear structure models and their description of the 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*

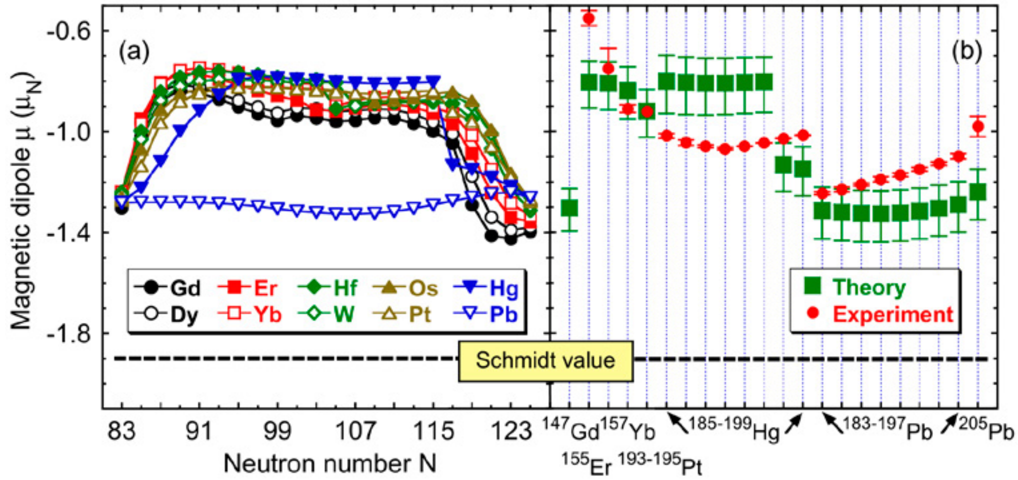
## ELECTROMAGNETIC MOMENTS IN HEAVY DEFORMED OPEN-SHELL NUCLEI

Within the nuclear DFT approach, we have determined the nuclear magnetic dipole and electric quadrupole moments for a large portion of the nuclear chart [1]. To obtain spectroscopic moments, we performed angular momentum projection (AMP) to restore broken rotational symmetry. As a result, we obtained good agreement with data without using effective g-factors or effective charges in the dipole or quadrupole operators, see Fig. 1. We also showed that the intrinsic magnetic dipole moments, that is, those obtained without AMP, do not represent viable approximations of the spectroscopic ones.

## IMPLEMENTATION OF ANGULAR MOMENTUM PROJECTION ON DFT SOLVER

We have implemented angular momentum projection on the HFBTEMP DFT solver. The HFBTEMP code solves the Hartree-Fock-Bogoliubov equations in axial basis, without assuming time-reversal symmetry. This allows proper treatment of various polarization effects in odd nuclei and computation of spectroscopic electromagnetic moments for deformed, open-shell nuclei.

[1] J. Bonnard, J. Dobaczewski, G. Danneaux, M. Kortelainen, *Nuclear DFT electromagnetic moments in heavy deformed open-shell odd nuclei*, Phys. Lett. B 843, 138014 (2023).




↑ Figure 1. Calculated magnetic dipole moments in odd-N nuclei (a) and comparison to available experimental data (b) [1].

# RADIATION EFFECTS

**Staff scientist Heikki Kettunen**
**University researcher Arto Javanainen**

**We are specialized in applied research around nuclear and accelerator-based technology and operate the Radiation Effects Facility, RADEF, for the studies of radiation effects in electronics and related materials.** RADEF officially became an ESA supported European Component Irradiation Facility (ECIF) in 2005. Since then, we have carried out irradiation tests not only for ESA and the European space industry, but also for other world leading space organizations (e.g., NASA, JAXA, CNES), companies and universities. A new five-years cooperation agreement, now under ESA's Tecnology Development Element (TDE), was signed at the beginning of 2023, covering the period 2023–2027.

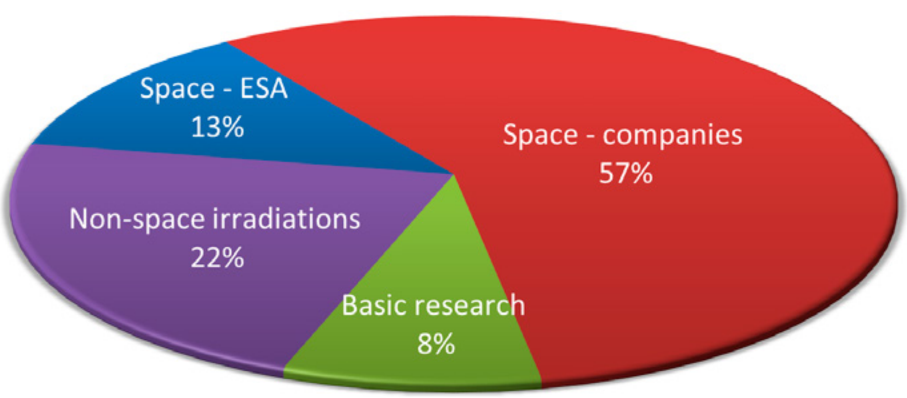
*www.jyu.fi/accelerator/radef*

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

RADEF used 1369 hours of K130-cyclotron beam in 64 campaigns with 25 different companies, institutes, and universities in 2023. This corresponds to 23 % of the K130 beam time hours. The distribution of this beam time between different users is shown in Figure 1. The total revenue of RADEF (commercial, EU and ESA projects) was about 1.3 M€ in 2023.

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

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



#### PROTON ENERGY DEPENDENCE OF SIC POWER MOSFET SINGLE EVENT BURNOUT SENSITIVITY

Wide bandgap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) have widely gained interest in power electronics applications due to their superior material properties over silicon (Si). They have high critical electric field, high thermal conductivity and high melting point which are all favorable properties where high power density is needed. For example, the space industry would greatly benefit from adoption of WBG components in their applications such as electric propulsion or power conditioning units. Moreover, the automotive industry is rapidly transitioning away from combustion engines to fully electric vehicles, where high energy efficiency can be obtained by using WBG technologies. However, wider use of such technologies is still hindered by the radiation-induced reliability issues.

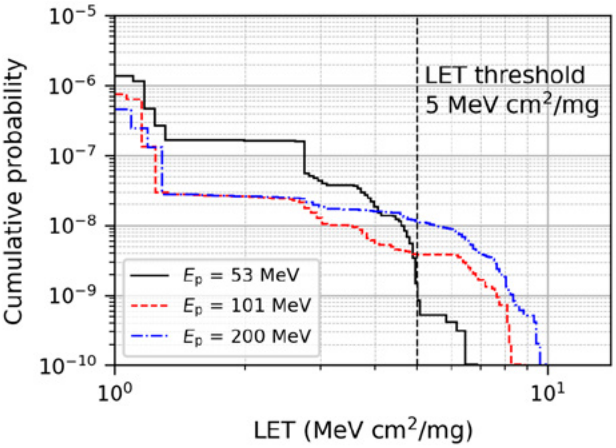
While being light particles, protons do not generate sufficient amount of charge by direct ionization in order to induce power device failure. However, the secondary particles created during interactions between the primary particle and the nuclei in target materials can induce significant energy deposition events in the device, and therefore result in a catastrophic failure of the power electronics component. The proton energies in Earth's orbits range from hundreds of keV up to hundreds of MeV and a single high energy proton strike can induce a catastrophic failure called single event burnout (SEB) in the power device.

The production and the transport of the secondary particles within the target structures are investigated through Monte Carlo simulations. The angle of incidence, penetration range and deposited energy and/or linear energy transfer (LET) of the secondaries are considered as the key parameters in terms of particle-induced failure. The Geant4 simulated secondary particle LET spectra for different primary proton energies are presented in Figure 2.

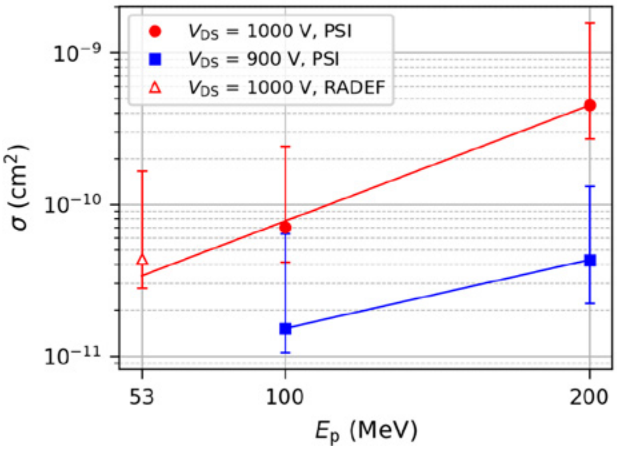
The SEB experiments for the SiC power MOSFETs were conducted at RADEF and Paul Scherrer Institute (PSI) in Switzerland. The 53 MeV proton beam from K130 cyclotron at accelerator laboratory and 100 MeV and 200 MeV proton beams at PSI were used.

As seen in Figure 3, the increase of proton energy from 100 MeV to 200 MeV increases the SEB cross section at $V_{DS}$ = 900 V and 1000 V by factor of 3 and 6 respectively. Moreover, at $V_{DS}$ = 1000 V, the SEB cross section for 200 MeV protons is approximately one order of magnitude higher compared to that for 53 MeV protons reported previously.

The increase in SEB cross section with increasing primary particle energy can be attributed to the higher probability of primary protons producing secondary particles with enough range and deposited energy to induce the burnout.




↑ Figure 2. Geant4 simulated complementary cumulative LET distribution of the secondary particles for different primary proton energies. Increasing primary proton energy Ep increases the count of high LET secondary particles. The vertical axis indicates the probability per primary particle.




↑ Figure 3. Proton energy dependence of the SEB cross section σ. 10 devices under test per primary proton energy configuration were used.

**Publication:**


K. Niskanen et al.,"Proton energy dependence of SiC power MOSFET single event burnout sensitivity", IEEE Nuclear & Space Radiation Effects Conference, Ottawa, Canada, 2024

**DEVELOPING ADVANCED HIGH-ENERGY X-RAY TOMOGRAPHY**

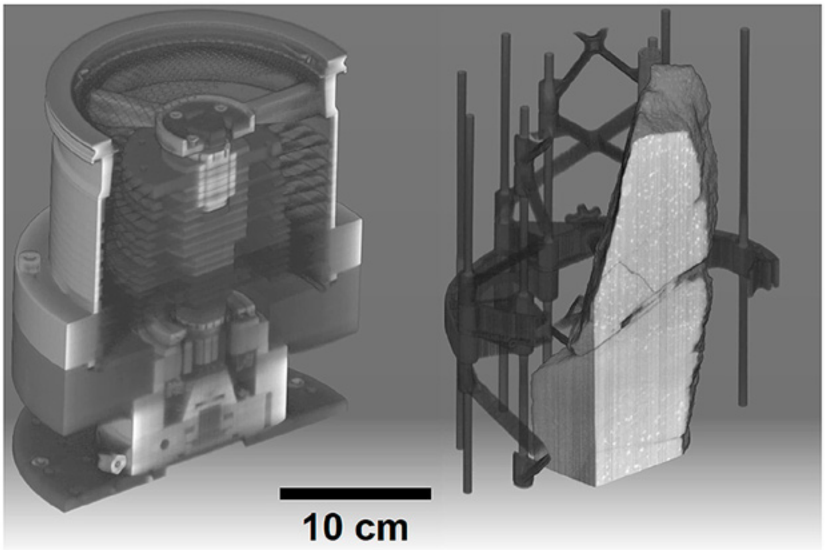
In collaboration with the Complex Materials Group, we have developed advanced high-energy X-ray tomography for internal structure imaging of large decimeter-scale samples using RADEF's recommissioned Varian Clinac medical linear accelerator. This state-of-the-art imaging system facilitates, for example, non-destructive evaluation of complex machinery and provides insights into the fracture networks of geological samples, as demonstrated in Figure 4.

Our involvement in geological sample imaging is part of the FLOP (Flow pathways within faults and associated fracture systems in crystalline bedrock) project. Through collaboration with the University of Turku, Åbo Academi and the Geological Survey of Finland, our department contributes to the detailed characterisation of bedrock fluid flow regulating fracture networks. The project aims to enhance understanding of hydrogeological processes which are crucial in risk analysis and development of underground nuclear waste repository concepts.

**EU PROJECTS**

**RADNEXT**

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




↑ Figure 4. Cross-sectional 3D reconstructions depicting the internal structures of two distinct objects captured through high-energy X-ray computed tomography. Left: A turbopump revealing intricate details of its inner structure. Right: A large crystalline bedrock sample in a custom 3D-printed sample holder showcasing its fracture network and dense mineral depositions.

# ION SOURCES

**Senior Lecturer Hannu Koivisto,**
**Staff Scientist Ville Toivanen**

**The ion source group develops ion sources and their beams for the users of the JYFL accelerator laboratory**. The group also conducts plasma research and development of plasma and ion beam diagnostics.

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

## PROGRESS OF THE CUBE PROTOTYPE

CUBE-ECRIS is a novel permanent magnet ion source prototype, which has been built to explore the feasibility and potential benefits of an unconventional quadrupole minimum-B magnetic field structure for plasma confinement and heating. In 2023 the research activities with CUBE-ECRIS focused on further studying the beam formation with the slit extraction system and low energy beam transport. The quality of the extracted beams was also determined with systematic beam emittance measurements. The results of the experimental studies, which were part of the PhD work of S. Kosonen, were published in Ref. [1]. The effect of gas mixing and double frequency operation, which are widely used methods to optimize the ECR-heated plasma conditions to produce high charge state ions in conventional ECR ion sources, were also studied with the CUBE-ECRIS. The results show that these techniques provide significant performance improvements, and consequently this aspect will not be a hindrance for the further development of this B-field concept towards more powerful future ion sources [2].

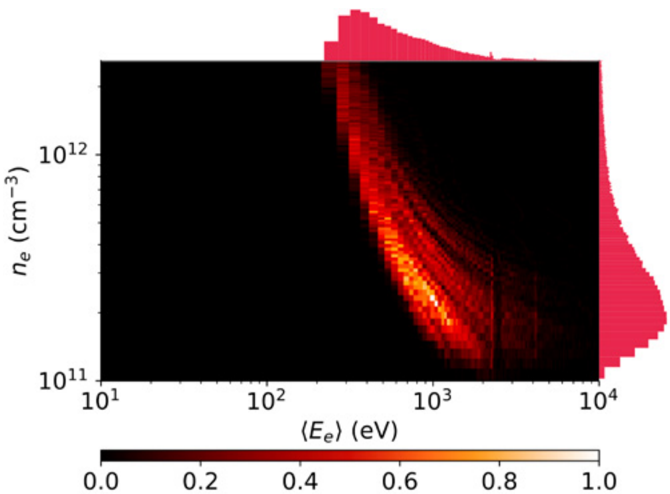
## ERIBS: EUROPEAN COLLABORATION ON ECR ION SOURCES

ERIBS (European Research Infrastructure – Beam Services) brings together participant research teams from nine different European laboratories developing ECR ion sources and their beams. The project focuses on the development of metal ion beam production techniques. As a new important collaboration concept, the expertise of the CNRS-IPHC team makes isotopically enriched compounds for ion beams available for the partner institutes. Several options to improve online monitoring of plasma instabilities and ion beam intensity variations have been selected for feasibility studies. The goal is to demonstrate that the monitoring system can provide relevant online data and information about the operating conditions and to aid the operator to maintain the required beam properties.

## RESEARCH AND DEVELOPMENT FOR ION SOURCES AND THEIR BEAMS

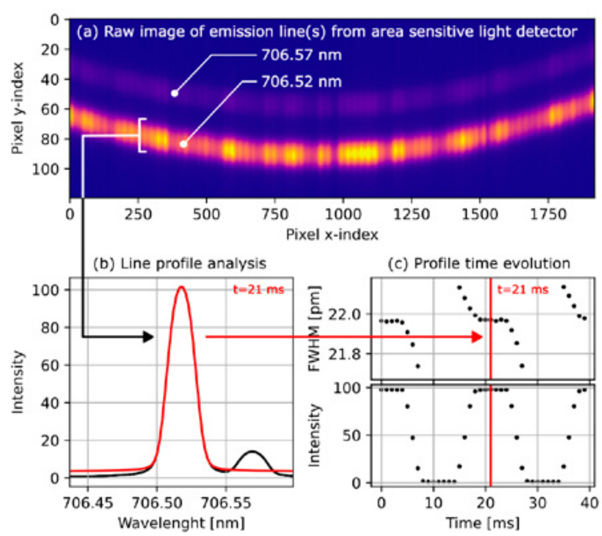
Several actions have been performed to improve the operation reliability and safety of the JYFL ion source facilities. Two new resistively heated miniature ovens have been constructed to increase operational reliability with metals and to minimize the contamination related challenges. The method used to produce calcium beams was also changed to improve a long-term beam stability and intensity. In the new approach metallic calcium is used instead of calcium oxide with reduction by zirconium. As a result of the R&D work higher beam intensities is achieved and better long-term beam stability is maintained. The radiation shielding of HIISI was improved to minimize the radiation dose of personnel and radiation sensitive components.

Miha Luntinen successfully finished his PhD work "Consecutive Transients (CT) Method for Plasma Diagnostics of Electron Cyclotron Resonance Ion Sources". He established a non-invasive method to study properties of highly charged plasma. The work was evaluated to be among the best 5–10 % of the cohort. The CT-method is based on pulsed injection of a stable isotope into a plasma sustained in the ECR ion source. Time behavior of several ion beams is recorded and used as inputs for the CT-method. A model-based optimization procedure is then used to seek out the electron density and average energy, as well as the characteristic times of ionization, charge exchange and ion confinement compatible with the measured time series. Figure 1 shows possible solution sets ($\langle E_e \rangle$-$n_e$) for $K^{9+}$ ions [3]. The $\langle E_e \rangle$ and $n_e$ distributions are projected on the margins of the figure. The number of possible solutions would decrease if the error related to the ionization cross sections could be decreased, and if appropriate multicomponent injection is used. The method also gives estimations for ionization, charge exchange and confinement times. Experimental campaigns at LPSC, France, confirmed that the CT-method is sufficiently sensitive to give relevant information about the plasma parameters when its condition is varied.




↑ Figure 1. Possible solutions sets ($<E_e>$-$n_e$) for $K^{9+}$ ions. The $<E_e>$ and $n_e$ distributions are projected on the margins of the figure.

The development and commissioning of the upgraded visible light spectrometer POSSU, which is designed to provide time-resolved light emission diagnostics with world-class spectral resolution for studies of temporally varying plasma phenomena, continued during 2023. The capabilities of the measurement setup have been broadened by implementing a more seamless use of both area sensitive and PMT-type detectors, and further improving the data analysis and post-processing abilities. An example of the analysis of measured helium emission line is presented in Fig. 2. The performance and abilities of POSSU were demonstrated in an experimental campaign where the temporal evolution of emission line profiles was measured during shifting elemental composition of ECR-heated ion source plasma with time resolutions that allowed the observation of both the gradual drift in the plasma parameters, and the detection of fast plasma instabilities taking place during the shifting conditions. From this data several plasma related parameters, e.g. the evolution of population temperatures of different plasma ion species, were determined during the varying plasma conditions. The study, which is part of O. Timonen's PhD work, is presented in Ref. [4].




↑ Figure 2. An example of time-resolved measurement of He I emission line at 706.52 nm from a pulsed gas discharge. (a) The measured emission line at the area sensitive detector (with a second dimmer emission line at 706.57 nm), (b) the resulting analyzed profile shape at the chosen time step (t=21 ms in this case), and (c) the variation of the profile intensity and width over the measured time window (40 ms in this case).

**Selected publications**


[1] S. Kosonen, T. Kalvas, H. Koivisto, O. Tarvainen and V. Toivanen, Nuclear Inst. and Methods in Physics Research, B 546 (2024) 165147.

[2] V. Toivanen, T. Kalvas, H. Koivisto, S. Kosonen and O. Tarvainen, accepted for publication in Journal of Physics; Conference Series (IOP/JPCS).

[3] M. Luntinen, J. Angot, H. Koivisto, O. Tarvainen, T. Thuillier, V. Toivanen, Phys. Plasmas, 30, (2023), p. 073904.

[4] O. Timonen, H. Koivisto, R. Kronholm and V. Toivanen, accepted for publication in Journal of Physics; Conference Series (IOP/JPCS).

# ACCELERATOR BASED MATERIALS PHYSICS

**Professor Timo Sajavaara**
**Academy Research Fellow Mikko Laitinen**
**Senior Lecturer Jaakko Julin**
**Senior Lecturer Kai Arstila (1.9.–31.12.)**

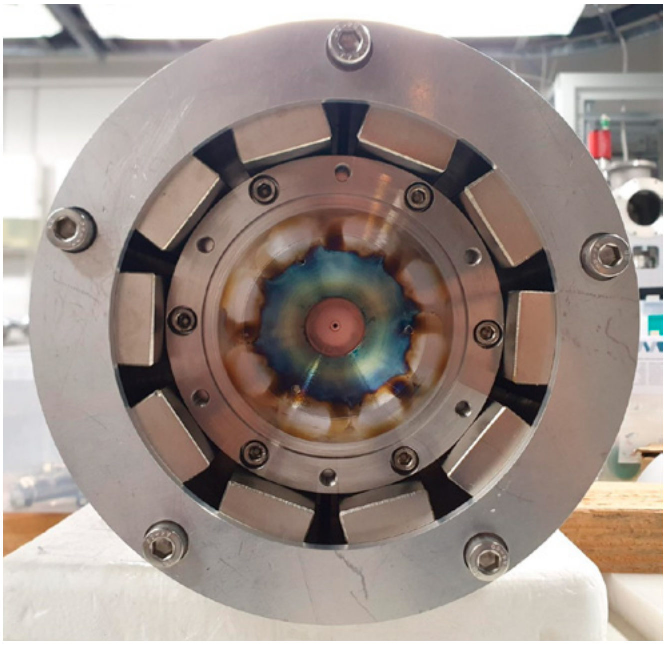
**The research activities of the group can be divided into four main areas: i) fundamental studies of ion–matter interactions, ii) detector, data acquisition and analysis software development iii) materials and especially thin film research and iv) applications of ion beam techniques for materials studies.** 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 two versatile atomic layer deposition (ALD) tools. The group is an active link between the two research infrastructures, Accelerator Laboratory and Nanoscience Center.

*https://www.jyu.fi/en/research-groups/accelerator-based-materials-research*

#### NEW OPENINGS AND GROUP MEMBERS

In 2023 we welcomed three new group members, PhD students Rebekka Nagy and Jaana Tiainen together with postdoc Olga Beliuskina – and said farewell to long term members of the group: University lecturer Kai Arstila (now in VTT Espoo) and Spyridon Korkos (in University of Helsinki). Spyridon defended his PhD thesis in March 2023.

Rebekka started her work in the microalphatross project, in which the goal is via systematic studies to produce a high intensity negative He ion source (see Fig. 1). In 2026 a new 3 MV tandem accelerator, and a new neutron beamline attached to it, will be installed. In her PhD project, Jaana studies a new neutron detector concept under supervision of our senior group members and Professor of Practice Kari Peräjärvi (20% JYFL, 80% STUK). Olga on the other hand tackles how to detect the low energy hydrogen ions in the ToF-ERDA system despite the bending trajectories in the electric fields of the timing gates. One significant research facility development in 2023 was the installation of a new sputtering ion source ionizer housing. This housing, together with the automation of the MC-SNICS ion source, has stabilized the ion beam currents from the source and thus greatly increased the usability of the Pelletron accelerator for research.



↑ Figure 1. Microalphatross He- ion source plasma chamber.

← Figure 2. Photo of the group in Pelletron laboratory in summer 2023.

## LASER-ASSISTED ION PRODUCTION

When a laser light is shone to a sputtering ion source, more negative ion beam can be extracted from it. Contrary to the earlier claims, we proved that resonant ion pair production is not significant, and any laser wavelength can be used [1]. This opens a way to modify the Cs coverage in the negative ion sources so that the ion source extraction current can be fine-tuned by means of laser light. In 2023 a patent application was filed by us for this process. The laser assisted fine-tuning of Cs coverage is potentially useful also in the high power, high intensity negative hydrogen ion sources, as it gives additional feedback loop tool to compensate beam intensity fluctuations.

## ION BEAM INDUCED NANOPARTICLE MODIFICATION

Swift heavy ion (SHI) irradiation effectively shapes embedded nanoparticles, controlling their size, shape, and orientation. In our recent study [2] randomly oriented gold nanorods in $SiO_2$ re-oriented or formed protrusions (Fig. 3) along the ion beam direction based on irradiation conditions and nanorod initial size. SHI also elongated spherical metallic nanoparticles in $Al_2O_3$, like those in $SiO_2$. Metallic nanostructures within dielectric matrices exhibited localized surface plasmon (LSP) modes. Dark-field spectroscopy of elongated nanoparticles revealed two discrete peaks corresponding to longitudinal and transverse modes.

## DELIVERY OF TOF-ERDA SPECTROMETER TO SLOVAKIA

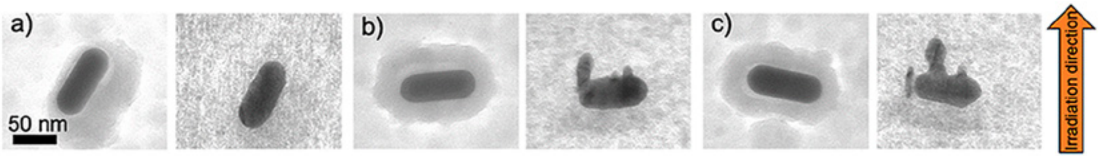
In June 2023, just after nine months of getting the official purchase order, we delivered a truly state-of-the-art, complete ToF-ERDA spectrometer beamline to TFU Trnava, University of Bratislava. This was the largest delivery of these systems from us with the contract price of about 750 k€. The fully automated spectrometer reached the highest-ever hydrogen detection efficiency – being about 50% for 500 keV hydrogen ions. The commercial activities like this enable more research and investments in JYFL, and for example the development of the Microalphatross ion source is partially covered with this income. In addition, the external funding enables more resources for our own ToF-ERDA development. This includes new Jyväskylä ToF-ERDA research tool (to be completed in 2024) and importantly the development of the Potku analysis software (new release versions in 2023).

**Selected publications:**

[1] A. Hossain et al, Photo-assisted Cl-, Br-, and I- production in caesium sputter ion source, 2023 JINST 18 C07002.
*https://doi.org/10.1088/1748-0221/18/07/C07002*

[2] S. Korkos, K. Arstila, K. Tapio, S. Kinnunen, J.J. Toppari, T. Sajavaara, Elongation and plasmonic activity of embedded metal nanoparticles following heavy ion irradiation, RSC Adv., 13, 5851(2023).
*https://doi.org/10.1039/D3RA00573A*

[3] S. He, A. Bahrami, X. Zhang, J. Julin, M. Laitinen, K. Nielsch, Low-temperature ALD of highly conductive antimony films through the reaction of silylamide with alkoxide and alkylamide precursors, Materials Today Chemistry. 32 (2023) 101650.
*https://doi.org/10.1016/j.mtchem.2023.101650*




↑ Figure 3. TEM images of chemically synthesized nanorods with similar size embedded in 100 nm PECVD $SiO_2$ and irradiated with 50 MeV $^{127}I$ at $10^{14}$ ions per $cm^2$ before (left) and after (right) the irradiation. Some nanorods still cannot elongate (a), but the formation of random protrusions/spikes on several nanorods was observed as well (b and c).

# CENTER OF EXCELLENCE IN QUARK MATTER

**Professor Tuomas Lappi**
**CoE director**

The second year of the CoE funding period was the first one with the research work really in full swing during the whole year. The new team members had gradually joined during the previous year, arriving by the end of October and settling in Jyväskylä by the winter. The enthusiastic presence of these new team members was really felt as a spirit of activity. This showed up in the number of publications reaching a new record for the theory group (for ALICE the total publication count is not a meaningful measure of our own activity). It also showed up in the large number of conference talks, posters and proceedings by the CoE members. In fact, the conference season was so busy that the travel activity associated with the international reach of our work raised some eyebrows, even at higher levels in the department and faculty.

A particularly heartening reward and recognition of work done in the previous years was the exceptional number of completed PhD's. Five graduate students finished their degrees during 2023, before or right after the summer vacations. Elsewhere within the department there had been some lamentation concerning the small audiences present in PhD defences. This did not apply to us: the department secretary soon learned that if the doctoral candidate is a member of the CoE, a double order of cake and coffee after the public defence is warranted.

After a successful first experience in the previous year, we again made an excursion to the dark but snowy November of the Finnish countryside at Konnevesi research station. The two-day retreat of over 30 people, full of physics discussions, outdoor activities, sauna and free discussions was again a very good experience. One innovation was the junior-only session that allowed us to get feedback on how our work is organized and what could be done better. Among the several things to result from this session was the need to more systematically share experiences and tools for different aspects of coding and scientific computing. This is being implemented in the form of "CoE computing afternoons" during the spring.

At the very end of the year we heard a piece of excellent news: Heikki Mäntysaari was awarded an ERC Consolidator Grant starting from the summer of 2024. The grant, entitled "Shining light on saturated gluons" (GlueSatLight) focuses on the physics of the future Electron-Ion Collider (EIC), which is being constructed at Brookhaven and should start taking data in the next decade. The EIC physics goals are very complementary to the LHC, and it was already a significant part of the research program of the theoretical research part of the CoE. With this new grant and the postdocs and students financed by it, this will be the case even more.

↑ Personnel of the CoE at the Konnevesi research station, November 2023

# QCD THEORY

**Professors Kari J. Eskola and Tuomas Lappi**
**Associate Professor Heikki Mäntysaari**
**Senior Lecturer Hannu Paukkunen**
**Academy Research Fellow 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://research.hip.fi/qcdtheory/*

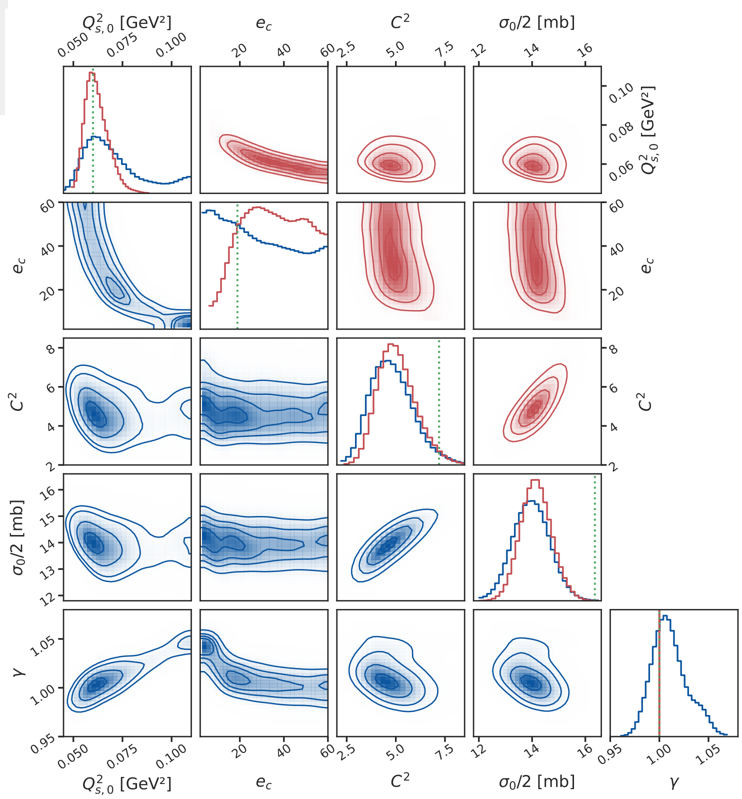
In 2023, the second year of our CoE, Felix Hekhorn, Xuanbo Tong, and Ismail Soudi started as new postdocs. Carlisle Casuga, Patricia Gimeno Estivill and Sami Yrjänheikki started as new PhD students. Postdocs Jarkko Peuron and Marius Utheim moved to the private sector, and postdoc Manuel Epele to a position at U. Nacional de La Plata. Jani Penttala defended his PhD thesis and moved to a postdoc position at the UCLA. Sami Demirci and Topi Löytäinen defended their PhD theses and moved to the private sector. At the end of the year, Heikki Mäntysaari was awarded an ERC Consolidator Grant.

### NON-LINEAR QCD AT HIGH ENERGIES

Over the last couple of years, we have been developing calculations within the Color Glass Condensate framework to the next-to-leading order (NLO) accuracy. This enables us to perform precision level calculations of various observables taking into account non-linear saturation effects. In 2023, we completed the first fully consistent NLO calculation of inclusive pion production in forward proton-lead collisions, demonstrating the possibility to include high-energy LHC data in precision analyses looking for signals of gluon saturation. [1]

In addition to higher order corrections, precision level calculations require an accurately determined initial condition for the perturbative high-energy evolution equations. We performed the first extraction of this initial condition, describing the proton structure at moderately small momentum fraction x, with a rigorously defined uncertainty estimate. This makes it possible to also estimate the uncertainty (Figure 1) due to the non-perturbative input when computing e.g. predictions for the LHC or for the Electron-Ion Collider (EIC). [2]

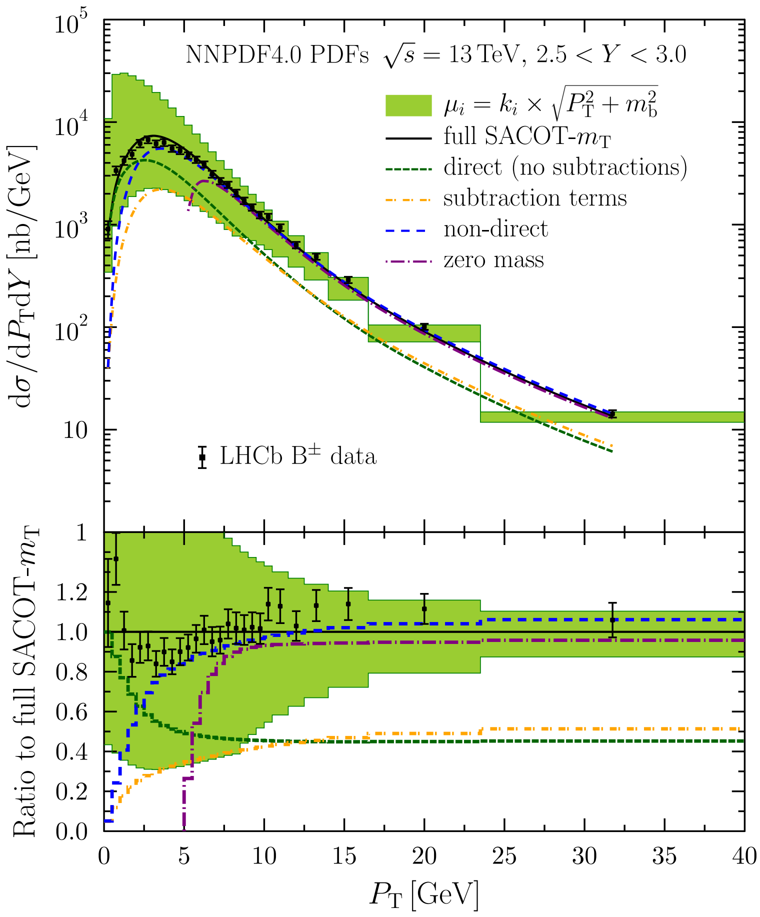
One particular focus of our group is exclusive vector meson production in ultraperipheral collisions at the LHC and at the future Electron-Ion Collider. We showed that this process can be used to probe the deformed nuclear geometry at high energy and emphasized the importance of accurately describing nuclear geometry when interpreting existing and future measurements. [3]




↑ Figure 1. Projections of the posterior probability distributions for parameter values from the Bayesian fit in Ref [2].

**HEAVY-QUARK PROCESSES AT THE LHC AND PARTON DISTRIBUTIONS**

During 2023 we have continued our theoretical studies on inclusive and exclusive heavy-quark processes at the LHC from the perspective of global analysis of parton distribution functions (PDFs) of protons and heavier nuclei. Concerning the inclusive reactions, we have extended our SACOT-mT scheme developed originally for charm-quark production in proton-proton and proton-lead collisions to the bottom-quark case [4]. Here, the agreement with the data measured at the LHC (Figure 2) gives confidence to the use of these type of data in future global fits of PDFs of protons and heavier nuclei. Concerning the exclusive processes, we updated our predictions for the coherent charm-anticharm bound-state production in ultraperipheral lead-lead collisions at the LHC with the latest PDFs and improved the theoretical ingredients, as well as made predictions for this process in ultraperipheral oxygen-oxygen collisions [5]. We also provided estimates for bottom-antibottom bound-state production in ultraperipheral collisions [6]. Our group has continued active participation in international high-energy physics collaborations through key representatives and developers in the PYTHIA, NNPDF and nCTEQ collaborations.



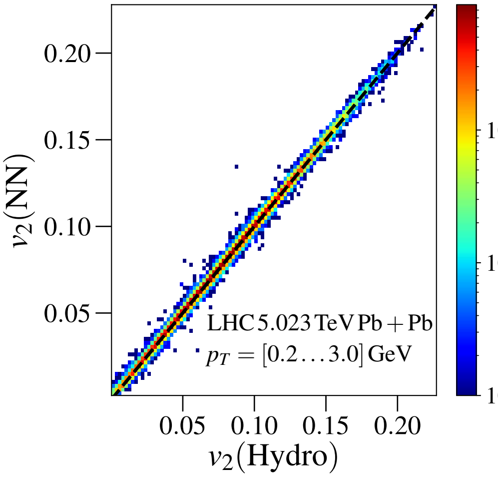

↑ Figure 2. Comparison of the calculation of Ref. [4] with LHCb measurements of B-meson production.

### HYDRODYNAMIC SIMULATIONS

One of the goals in the ultrarelativistic heavy-ion collision experiments at the CERN-LHC and BNL-RHIC colliders is to determine the properties, like viscosities, of strongly interacting QCD matter. Their extraction from the measurements requires a good understanding of the nuclear collision and QCD matter dynamics. A central tool here is relativistic hydrodynamics.

Performing event-by-event hydrodynamic simulations with a similar level of statistics as in the experiments is computationally demanding. To this end, in 2023, we constructed the very first set of neural networks that can predict hydrodynamically computable final observables directly from the initial energy-density profile [7], see Fig. 3. Particularly, with weak flow-correlators whose precision study requires millions of collision events, the neural networks can speed up the computation significantly. We also extended our networks to take the QCD matter properties as input [8], removing the need to train a new set of networks for each set of matter properties. These networks can reduce the computation time in the extraction of QCD matter properties via a global analysis by several orders of magnitude.

Event-by-event fluctuations of initial state densities play a crucial role in the collision dynamics. To describe such initial conditions for the full 3+1 D hydrodynamics, we are developing a new perturbative QCD based Monte-Carlo EKRT event generator. The new MC-EKRT framework, which includes fluctuations of minijet production together with saturation and overall energy conservation event by event, allows us to study QCD matter evolution in small systems and rapidity-dependent observables.




↑ Figure 3. Validation of the event-by-event neural network (NN) predictions against the hydrodynamical results for elliptic flow. Figure from [7].

### PRE-EQUILIBRIUM TRANSPORT COEFFICIENTS

Hard probes such as jets and heavy quarks are a valuable tool to probe the properties of deconfined quark matter. One particularly important aspect of such hard probes is that they can provide direct experimental signals also from the earlier stage of the spacetime evolution of the plasma, and not just the final freezeout surface where most of the measured particles are produced. Until now, most groups simulating the interactions of jets and heavy quarks with quark matter have restricted their attention to a thermal quark gluon plasma, leaving out the earliest pre-equilibrium stage where the plasma energy density is the largest. In a series of four papers [9] resulting from several years of work we performed a systematical kinetic theory calculation of "transport coefficients" measuring the momentum transfer to heavy quarks and jets in the pre-equilibrium stage. In addition to being useful for modeling jet and heavy quark observables, these calculations shed new light on the interpretation of universal pre-equilibrium attractor feature of the equilibration process of the plasma.

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[1] H. Mäntysaari, Y. Tawabutr, Phys. Rev. D 109 (2024), 034018

[2] C. Casuga, M. Karhunen, H. Mäntysaari, Phys. Rev. D 109 (2024), 054018

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[4] I. Helenius, H. Paukkunen, JHEP 07 (2023) 054

[5] K. J. Eskola, C. A. Flett, V. Guzey, T. Löytäinen, H. Paukkunen, Phys. Rev. C 107 (2023) 4, 044912

[6] K. J. Eskola, C. A. Flett, V. Guzey, T. Löytäinen, H. Paukkunen, Eur. Phys. J. C 83 (2023) 8, 758

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# ALICE EXPERIMENT AT THE CERN LHC

**Senior Lecturer Sami Räsänen and**
**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 physics program includes proton, lead, and oxygen collisions. ALICE can track and identify particles down to low transverse momenta, allowing detailed studies of the essential properties of the QGP.

Currently, the Finnish group has major responsibilities in the maintenance and operation of the Fast Interaction Trigger (FIT) detector, and we also participate actively in the forward calorimeter FoCal upgrade. In physics analysis, we concentrate on collective phenomena and jets.

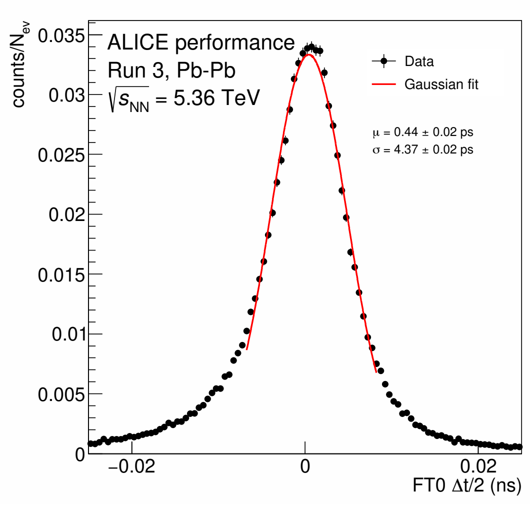
ALICE collaboration has ≈1950 members from 169 institutes in 40 countries. JYFL and HIP have been ALICE members since November 1997. ALICE activities in Jyväskylä are part of the Centre of Excellence (CoE) in Quark Matter at the Finnish Academy.

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

In 2023, the upgraded ALICE experiment collected a sizable proton-proton sample and 12 billion lead-lead collision events during a five-week-long heavy ion run. We gained 40 times the statistics collected in all previous heavy ion runs between 2010 and 2018! Compared to other large LHC experiments, ALICE uses triggerless data collection to study, e.g. thermal electromagnetic radiation or heavy-flavored hadrons down to low momenta, where QGP medium effects are more pronounced.

ALICE underwent our high-luminosity upgrade during the previous long maintenance break of the LHC running, and 2023 was the second year of operation of a thoroughly modernized experiment. The upgraded detector works very well, and after an intensive calibration effort, the first physics results were released at conferences.

One of the new detectors in the running experiment is the Fast Interaction Trigger (FIT) [1]. FIT delivers triggers for the detectors that need them, provides online luminosity monitoring, a precise collision time and an unbiased sample of the forward multiplicity required to extract the centrality and the reaction plane of the colliding heavy ions. Our group has been responsible for FIT since 2013, when we proposed the new detector to the ALICE collaboration, and we coordinate the work of scientists representing 17 institutions from 8 countries.




↑ Figure 1.Excellent collision time resolution σ=4.37±0.02 ps with FIT.

We contribute to FIT software development, take expert shifts, and monitor and mitigate detector ageing. We, for example, study centrality and event plane determination with FIT. Figure 1 demonstrates an excellent σ=4.37±0.02 ps timing resolution in the collision time measurement in Pb-Pb collisions with FIT! Good timing resolution is pivotal for particle identification using time-of-flight in ALICE. Excellent particle identification is needed, e.g. to study the chemical composition of the created QGP droplet.

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.

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 analyze the azimuthal particle distributions using Fourier expansion. The extracted Fourier "flow" coefficients are related to the transport properties of the QGP. In 2023, we measured correlations between different flow coefficients that, based on theoretical models, are sensitive to the transport properties of the QGP [2].

An intriguing question in heavy ion physics is to search limits of the QGP production when the size of the fireball gets smaller. Figure 2 shows that one finds non-zero flow coefficients in pp and p-Pb collisions [3]. This measurement was challenging due to a large background from jets in the small systems. The final word is yet to be said on whether these non-zero Fourier modes can be related to collective flow due to the presence of QGP in these collisions!

ALICE is preparing for the next upgrades, namely a new forward calorimeter (FoCal) and upgraded vertex detector (ITS3). FoCal will be placed outside the main ALICE magnet at small scattering angles, 7 m from the interaction point. FoCal reached several milestones in 2023. ALICE released a public note on the physics of FoCal [4], which included significant input from the CoE theory groups. We released a note on the expected performance of FoCal [5], where our group contributed to studies of the response of the calorimeter, neutral pion reconstruction, and performance in correlation and jet measurements. FoCal prototypes have undergone a series of test beam campaigns, and results were collected into a publication [6]. We participated in data taking and analysis of the test beam data.

In December 2023, the Research Council of Finland made a favorable funding decision for the joined CMS-ALICE infrastructure application for the upcoming detector upgrades. The grant enables the acquisition of a new automated bonder for the HIP detector laboratory in Helsinki, allowing for detector element production on a large scale. The bonding of the pixel layers of the electromagnetic calorimeter in FoCal will be shared between laboratories in Helsinki, Oslo, and Wuhan. For the hadronic calorimeter in FoCal, our group studies the radiation tolerance of the proposed SiPMs and optical fibres, and contributes to the design of the laser calibration system.


[1] "The new ALICE Fast Interaction Trigger", W.H. Trzaska, https://www.youtube.com/watch?v=E5g5lOuJr1M

[2] ALICE Collaboration, PRC108 (2023) 055203

[3] CERN Courier, https://cerncourier.com/a/collectivity-in-small-systems-produced-at-the-lhc/

[4] ALICE Collaboration, https://cds.cern.ch/record/2858858/files/pubnote.pdf

[5] ALICE Collaboration, https://cds.cern.ch/record/2869141/files/pubnote.pdf

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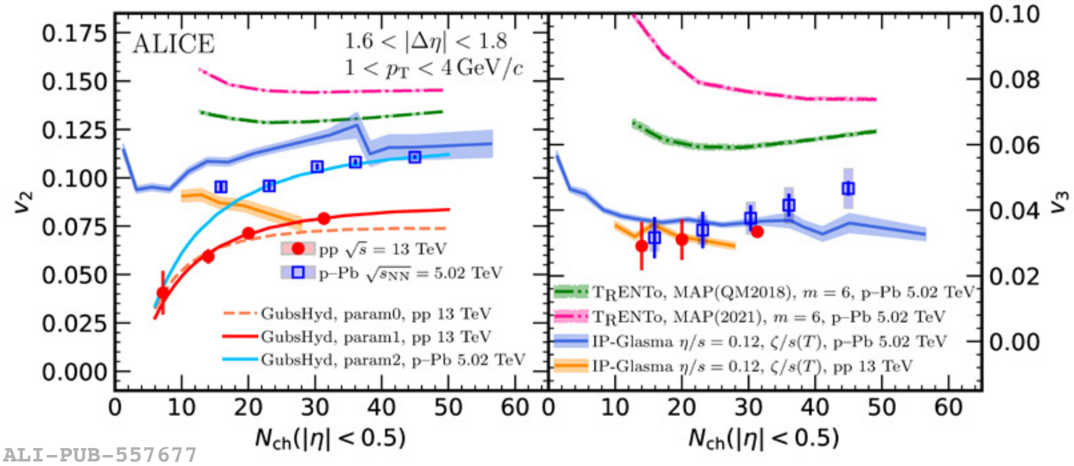
↓ Figure 2. Fourier coefficients measuring collective phenomena in pp and p-Pb collisions.

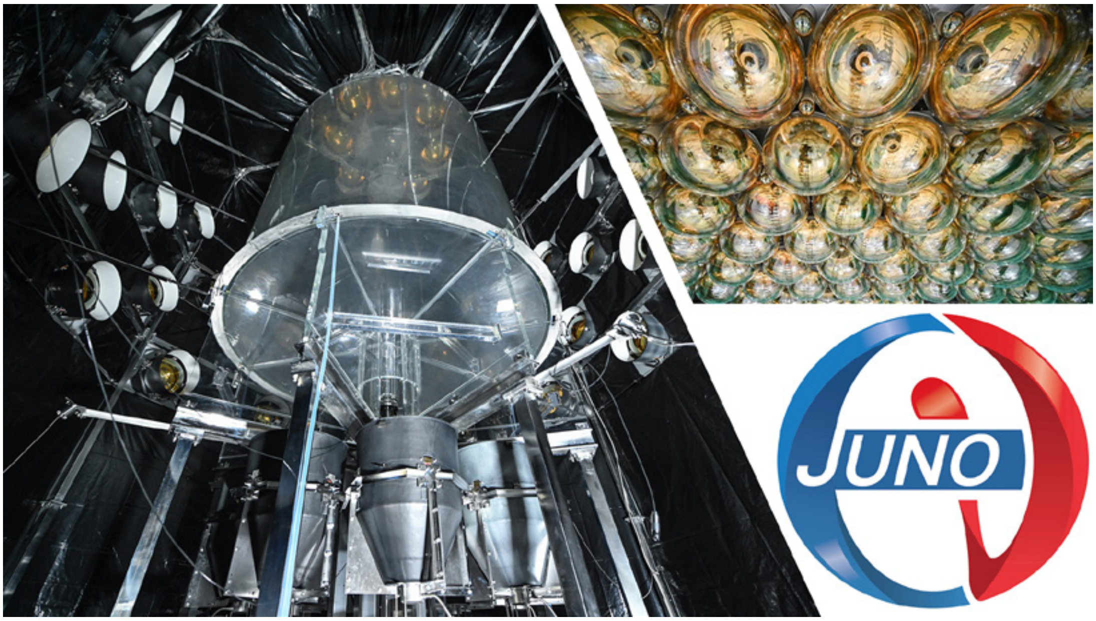


# NEUTRINO AND ASTROPARTICLE PHYSICS

**Senior Researcher Wladyslaw H. Trzaska**
**Postdoctoral Researcher Kai Loo**

**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.

NEMESIS 1.4 →




↑ Figure 1. Left – JUNO-OSIRIS setup – the standalone radiopurity detector for liquid scintillator screening before filling the Central Detector. Right – a small section of the JUNO Central Detector's 45 thousand PMT light sensors.

Installation of the JUNO Central Detector supported by a giant steel frame continued throughout 2023. The 35-meter diameter acrylic sphere, designed to hold 20 thousand tons of ultrapure liquid scintillator, is 64% ready. In parallel, the installation of 17,612 20" PMT and 25,600 3" PMT light sensors facing the sphere is ongoing. In addition, the surrounding water pool will be instrumented with 2,400 20" PMTs. Our team's main contribution comes through OSIRIS – the standalone radiopurity detector sampling 15% of each liquid scintillator batch before adding it to the central detector (Fig. 1). The construction and instrumentation of the OSIRIS detector have been completed, and by the end of 2023, we have moved to the commissioning phase. Light detection, calibration and data acquisition systems have been tested with dry runs. The first water filling of the detector was started in December. During next year, the commissioning and characterisation of OSIRIS will continue. For that purpose, the run coordination and analysis groups have been established. Kai Loo coordinates simulations and analysis. The filling of the central detector of JUNO is scheduled to start by the end of 2024. The first physics runs will take place in 2025.

After two years of excavations, the giant underground caverns for the DUNE neutrino experiment have been completed at the Sanford Underground Research Laboratory in Lead, South Dakota (Fig. 2). The design of the dedicated neutrino beamline complex at Fermilab, 1300 km away, is nearly completed. The first of the four planned detectors is expected to be commissioned by 2028. DUNE involves 1000 scientists from 200 institutions in 36 counties. Our main physics goal is to study long baseline neutrino oscillations, including precision measurements of oscillation parameters and identification of the neutrino mass ordering. The ultimate objective is to search for CP violation in the neutrino sector and measure the CP-violation phase. Discovering CP violation in the neutrino sector could answer the long-lasting mystery of the imbalance between matter and anti-matter in the Universe. Our team explores extending the low-energy capabilities of DUNE with a hybrid event detection technology, leveraging both Cherenkov and scintillation light simultaneously. We are also involved in feasibility studies for the indirect detection of Dark Matter at SURF.


← Figure 2. Top – bird's view of Lead, South Dakota and the decommissioned Homestake Mine. The 800,000 tons of excavated rock from the DUNE caverns were transported with a 1.3 km-long conveyor belt and deposited in the open pit. Bottom – one of the caverns ready to house DUNE liquid argon cryostats.

**Selected publications**

[1] The JUNO collaboration. (2023). JUNO sensitivity to 7Be, pep, and CNO solar neutrinos. Journal of Cosmology and Astroparticle Physics, 2023(10), Article 022.
*https://doi.org/10.1088/1475-7516/2023/10/022*

[2] The JUNO collaboration. (2023). JUNO sensitivity to the annihilation of MeV dark matter in the galactic halo. Journal of Cosmology and Astroparticle Physics, 2023(09), Article 001.
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[3] The JUNO Collaboration. (2023). The JUNO experiment Top Tracker. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1057, Article 168680.
*https://doi.org/10.1016/j.nima.2023.168680*

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*https://doi.org/10.1103/PhysRevD.107.112012*

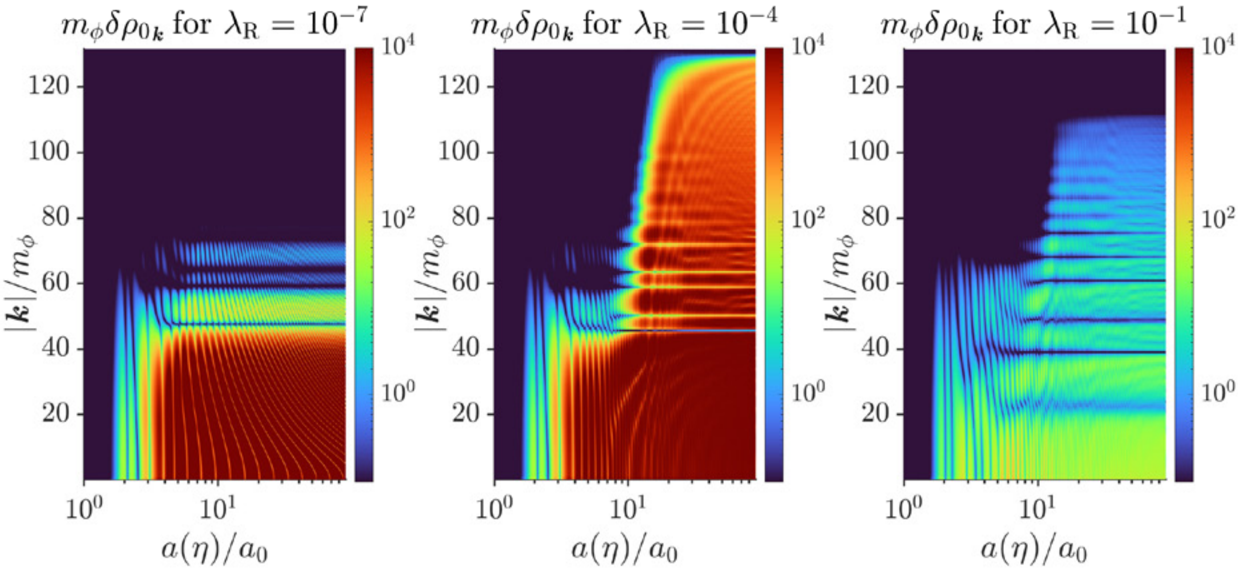
# COSMOLOGY

**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 apply them in our various research topics.

### DARK MATTER

About 26% of the total energy of the universe consists of a pressureless fluid, whose precise nature is not known. We study various candidates for the dark matter (DM), ranging from particle DM to primordial black holes. We were among the first to thoroughly investigate the idea of a dark sector connected to SM via scalar portal and we have shown that primordial physics during inflation and reheating can be connected to DM and its properties, testable by precision data on cosmic structures. This year we performed a non-perturbative quantum study of gravitationally driven tachyonic production of non-minimally coupled DM relics during reheating using the 2PI formalism in Hartree truncation [1], see Figure 1. We also initiated a new work comparing the quantum results against the outcomes of classical lattice simulations in the same setup.




↑ Figure 1. Momentum space structure and evolution of the two-point function of a DM scalar produced during reheating. The scalar is non-minimally coupled to gravity and the three panels correspond to different values of the scalar self-coupling. Figure is from [1].

## INFLATIONARY PHYSICS

Large scale structures in the universe seem to originate from inflation. We study the microscopical mechanism of the process and its connection to fundamental theories of matter and gravity. We in particular test and constrain extensions of the Standard Model of particle physics by studying the observational signals and theoretical constraints connected to primordial Higgs dynamics. We apply advanced quantum transport theory methods for precision study of various primordial processes, including non-perturbative infrared dynamics of light fields and particle production during inflation and reheating. This year we showed that inflationary fluctuations of spectator fields, such as the Higgs, could be extremely efficient in sourcing PBHs [2]. On a more conceptual front, we found that the well-known scale-invariant gravitational wave spectrum predicted by inflation is dominated by a subluminally propagating tail component [3]. A detection of primordial gravitational waves from inflation would therefore also serve as an indirect verification of the tail effect predicted by general relativity.

## BARYON ASYMMETRY

One outstanding problem in LCDM-model is the origin of the matter-antimatter asymmetry in the Universe. The observed asymmetry must be created after inflation by some microphysical process that involves new physics beyond the standard model of particle physics. The leading candidates are the leptogenesis and the electroweak baryogenesis mechanisms, which both involve interacting coherent quantum fields in CP-violating, out-of-equilibrium conditions. We are world leaders in deriving and applying quantum transport methods in these setups [4,5] and we are currently extending these methods into the fully quantum-mechanical regime, relevant for strong electroweak phase transitions, that could simultaneously source primordial gravitational waves.

## NEUTRINO PHYSICS

Light neutrinos are known to display intricate flavor mixing patterns, which are responsible for the solar and atmospheric neutrino anomalies and play a significant role for neutrino interactions in supernovae and in other compact objects. This year we derived the most general quantum kinetic equations (QKE) for neutrinos [6], which include both flavor and particle-antiparticle coherences and for the first time implement clear rules for computing collision integrals for and between coherently evolving states. We are currently applying these methods to model neutrino mixings in particle colliders and in astrophysical objects.

### Selected publications


[1] K.Kainulainen, O.Koskivaara and S.Nurmi, “Tachyonic production of dark relics: a non-perturbative quantum study”, JHEP **04** (2023), 043 doi:10.1007/JHEP04(2023)043.

[2] A.D.Gow, T.Miranda and S.Nurmi, “Primordial black holes from a curvaton scenario with strongly non-Gaussian perturbations”, JCAP **11** (2023), 006.

[3] N.Jokela, K.Kajantie, M.Laine, S.Nurmi and M.Sarkkinen, “Inflationary gravitational wave background as a tail effect”, Phys. Rev. D **108** (2023) no.10, L101503

[4] K. Kainulainen, “CP-violating transport theory for electroweak baryogenesis with thermal corrections”, JCAP 11 (2021) 11, 042.

[5] H. Jukkala, K. Kainulainen, P.M. Rahkila, “Flavour mixing transport theory and resonant leptogenesis”, JHEP 09 (2021) 119,

[6] K.Kainulainen, H. Parkkinen, “Quantum transport theory for neutrinos with flavor and particle-antiparticle mixing”, JHEP 02 (2024) 217.

# INDUSTRIAL COLLABORATION

**Senior researcher Arto Javanainen**
**Staff Scientist Heikki Kettunen**
**Academy Research Fellow Mikko Laitinen**

#### RADEF, THE RADIATION EFFECTS FACILITY

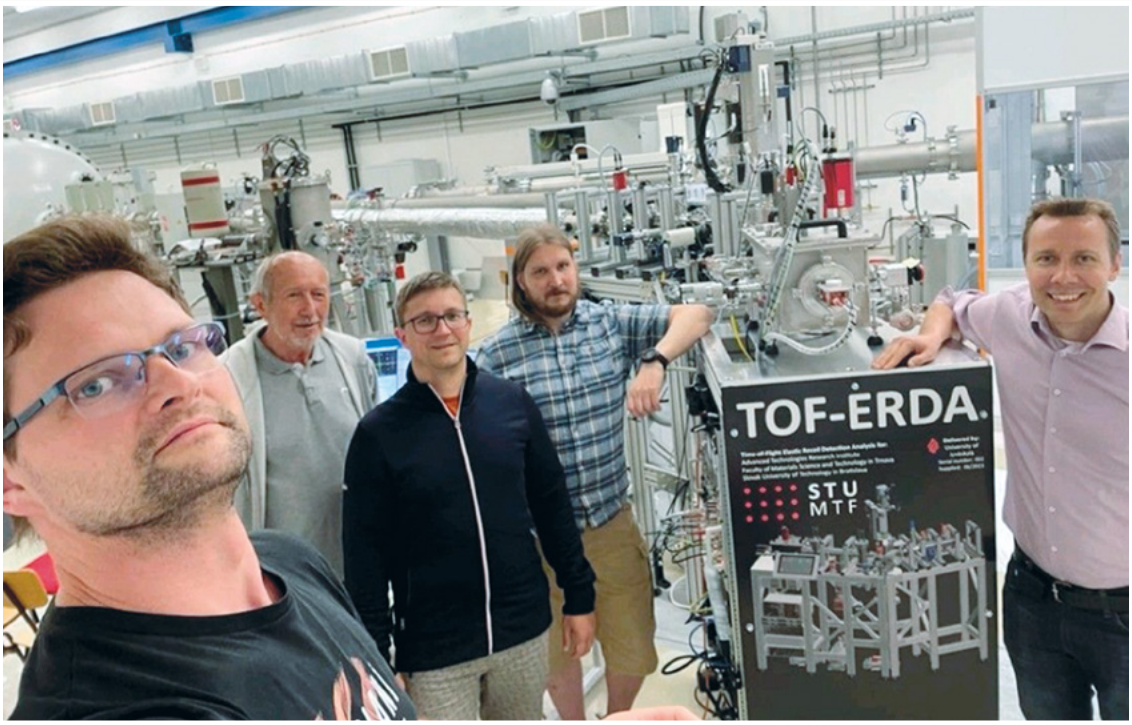
The Radiation Effects group of the Accelerator Laboratory continued the utilization of RADEF facility under ESA's Technical Research Programme (TRP) since 2005. A new five-years cooperation agreement, now under ESA's Tecnology Development Element (TDE), was signed at the beginning of 2023, covering the period 2023–2027. RADEF is specialized 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 provide K-130 cyclotron and cLinac electron accelerator beams, mainly for ESA and the European space industry for testing radiation hardness of electronic components. The use of RADEF's commercial beam time in 2023 was 1 369 hours corresponding to 23 % of the total running hours of the K-130 cyclotron. In total, 64 test campaigns for 25 different companies were performed at RADEF. The commercial revenue was about 1.3 M€ in 2023.

RADEF is involved in two EU projects. The Erasmus Mundus Joint Master Degree programme (RADMEP) and EU Horizon-2020 project called "RADiation facility Network for the Exploration of effects for indusTry and research" (RADNEXT) started in 2021.

#### TOF-ERDA

Accelerator based materials reseach group delivered a ToF-ERDA spectrometer to Slovakia in 2023. The total value of delivery was about 750 k€ (Fig. 1). The commercial activities included also more traditional ion beam analyses of samples for several companies. The multi-detector RBS system with enhanced solid angle/increased number of detectors enabled very small impurity concentrations or ultra thin films to be analysed better than ever before. Different type of XRF studies were also performed during 2023 and a new kind of X-ray imaging project was initiated. The intensity of these activities are seen to further increase with the 3 MV tandem platform arriving in 2026.

Radiation Protection Expert -service (RPE) generated stable revenue and the work became more efficient as the experience from the existing company cases can now be utilized for the larger user base. If RPE service would provide training courses as well, this could be a new income possibility. These courses are mandatory for the customer companies by the law.




↑ Figure 1. ToF-ERDA spectromenter delivered to University of Bratislava, in Trnava. This was the 2nd complete TOF-ERD system commercially build, delivered and on-site installed.

### BUSINESS NETWORKING DAY

The Department of Physics participated actively in the Business Networking Day of the University of Jyväskylä. The goal of the event was to bring together researchers, companies, and other stakeholders to find how the University could better contribute to the needs of the business environment regionally, and in the entire Finland. Business Networking Day was arranged in the Congress Center Paviljonki, and included talks and pitches from researchers and companies, exhibition of the stakeholders, poster session for research groups, and a networking dinner. The event attracted over 540 participants including representatives of nearly 60 companies and stakeholders, researchers from the University, and students seeking for future job opportunities. Success of this format is proved by several new university-company collaborations each year, so do not miss the 2024 event on 10th of October!

# TEACHER EDUCATION AND PHYSICS EDUCATION RESEARCH

**Professor Pekka Koskinen and**
**Senior Lecturer Antti Lehtinen**

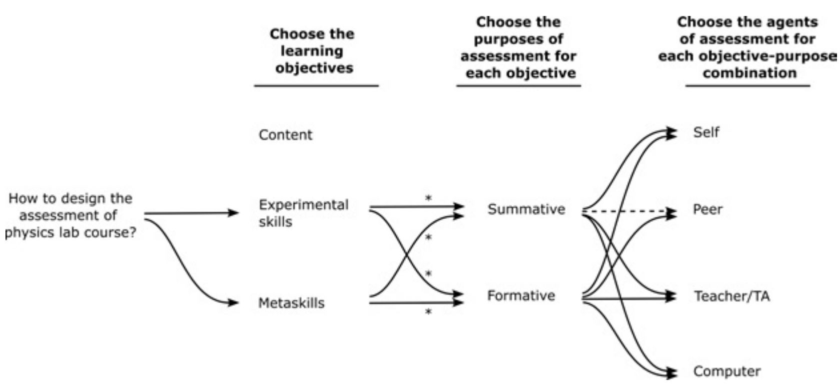
**We are passionate in developing the contents and instructional strategies of physics education and physics teacher education, to foster efficient physics learning and teaching at schools and universities and inspire young pupils to study physics.**

### HOW TO ASSESS PHYSICS LAB COURSES?

The development of physics instructional labs has attracted attention in recent years. Research has focused on learning goals and instructional methods in labs, but assessment of lab work has remained largely unexplored. As assessment is highly influential for learning, it should be a key element of lab work development. In collaboration with Laura Ketonen from the Department of Teacher Education, we conducted a literature review of research on assessment of lab courses with a special focus on the objectives, purposes, and agents of assessment [1]. Based on our review, assessment of instructional labs is summatively emphasized, instructor-led, and focused on experimental skills and physics content — in other words, traditional. To assist in modernizing the assessment practices of lab courses, we propose a design model for lab teachers (Figure 1).

### THE SCAN-METHOD AS A WAY TO SELF-ASSESS PHYSICS PROBLEM-SOLVING

The Solve-Correct-Assess-Negotiate (SCAN) -method (*ruotiminen* in Finnish) has gained a steady foothold as a routine assessment practice for the weekly problem sets at many courses at the Department of Physics. In the method, the students are provided with model solutions to the problems after a given deadline. The students use these solutions to identify and correct their own solutions. Moreover, they assess both their original and corrected solutions with the help of a rubric. This self-assessment is followed by group discussions with the teacher to identify possible issues. A recent publication delved into students' perceptions of using SCAN [2]. Even though the students relied more on teacher-led assessment than SCAN, those students who perceived SCAN as a beneficial assessment method adopted a deeper approach to learning and felt that they receive more support for learning. As the students' perception of the benefits of using SCAN correlated with their perception of SCAN as a reliable assessment method, more emphasis should be placed on discussing the utility and reliability of different assessment methods.



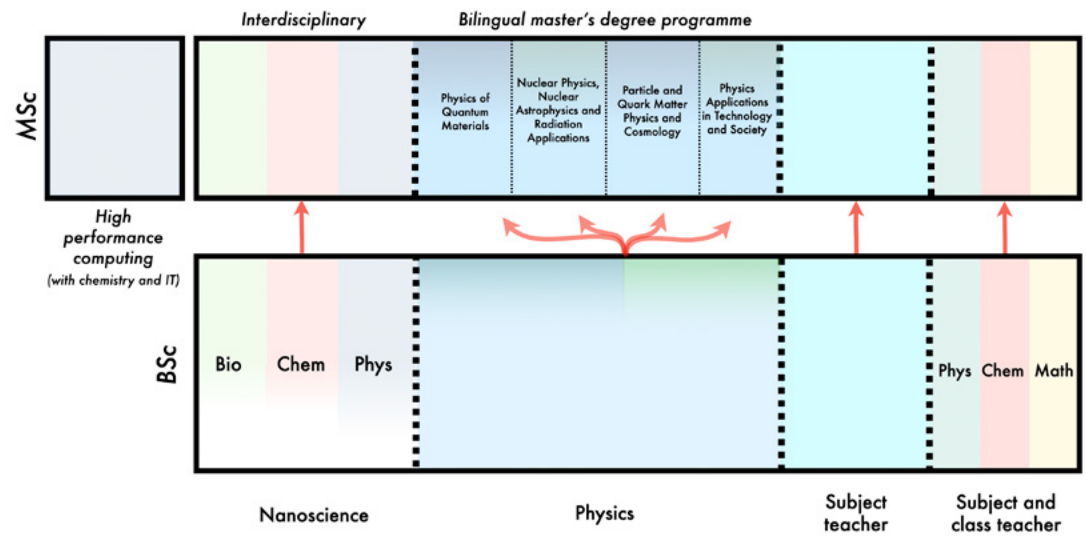

**Selected publications**

[1] L. Ketonen, A. Lehtinen, & P. Koskinen (2023). Assessment designs of instructional labs: A literature review and a design model. *Phys. Rev. Phys. Educ. Res.*, 19(2), 020601. *https://doi.org/10.1103/PhysRevPhysEducRes.19.020601*

[2] J. Lämsä, A. Virtanen, P. Tynjälä, J. Maunuksela, & P. Koskinen (2023). Exploring students' perceptions of self-assessment in the context of problem solving in STEM. *LUMAT*, 11(2). *https://doi.org/10.31129/LUMAT.11.2.2028*

# PHYSICS EDUCATION

**Professor Pekka Koskinen,**
**University Teacher Jussi Maunuksela**
**and Associate professor Heikki Mäntysaari**




↑ Figure 1. The new structure for physics degree programmes.

#### CURRICULUM RENEWAL

During 2023, we actively developed our new physics curriculum that will start in the fall 2024. The development work resulted in a substantial overhaul of the degree structure: we created an interdisciplinary nanoscience bachelor's degree programme, dedicated subject teacher bachelor's degree programme, and a bilingual master's degree programme with four field-specific study directions (Figure 1). In the new curriculum, physics will also be part of the subject and class teacher programmes, along with chemistry and mathematics. Moreover, physics will be involved in the completely new high performance computing international master's degree programme, together with chemistry and the faculty of information technology.

#### EMPOVERING STUDENTS' ENGAGEMENT IN THESIS WORK

Another field where we were actively developing teaching practices is the thesis writing process, especially for the bachelor's thesis. In order to empower students to take more active role in their thesis work, we organized a sparring meeting for students planning their thesis. The aim of this meeting was to encourage students to suggest and develop their own ideas for the topic of their thesis work. In the meeting students worked in small peer-groups mentored by PhD students. Based on their ideas and received feedback each student then determined and submitted a tentative topic for the thesis work. The other change in the process is that the department appointed thesis supervisors who are experts in the research and writing process – but not necessarily in the topic that is also aimed to encourage students take ownership of the thesis work.

#### INTERNATIONAL PHYSICS OLYMPIADS

The department coordinates Finnish participation in international physics competitions for upper secondary school students and organizes training camps for students chosen to represent Finland. In 2023, approximatively 20 students participated in Nordic-Baltic Physics Olympiad in Estonia, and the top 5 Finnish students were chosen to represent Finland at the International Physics Olympiad (IPhO) held in Japan. The Finnish and Estonian IPhO teams prepared for the experimental part of the IPhO by attending a week-long training camp organized at the physics department.

# RESEARCHERS' NIGHT

**Janne Pakarinen, Arttu Miettinen**


**In the darkness of September 2023, the Department of Physics participated in the traditional University-wide Researchers' Night event.** The Department featured activities for pre-school and school kids, HEPScape escape room game, open doors night in the Accelerator Laboratory, and 3D X-ray imaging workshop, accompanied by presentations about particle physics, quark matter and the timeline of the universe. VTT Technical Research Center of Finland showed a movie about "collisions and flows" and presented their work on sustainable bio-based materials with various demonstrations. Finally, Sirius Jyväskylä demonstrated remote access to their observatory located in Hankasalmi. In total, our activities attracted a record-breaking 3 765 science-hungry visitors!

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

**Department of Physics**

FACULTY OF MATHEMATICS AND SCIENCE

P.O. Box 35, FI-40014 University of Jyväskylä,
Finland

jyuscience.fi
JYUscience
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